US010119881B2

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Takeda

(10) **Patent No.: US 10,119,881 B2**
(45) **Date of Patent: Nov. 6, 2018**

(54) **METHOD AND APPARATUS FOR DETECTING GAS LEAKAGE FROM RADIOACTIVE MATERIAL SEALED CONTAINER**

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(73) Assignee: **CENTRAL RESEARCH INSTITUTE OF ELECTRIC POWER INDUSTRY**, Tokyo (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 493 days.

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(65) **Prior Publication Data**

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(30) **Foreign Application Priority Data**

Sep. 16, 2015 (JP) 2015-182926

(51) **Int. Cl.**

G21F 5/00	(2006.01)
G21F 5/012	(2006.01)
G21F 5/06	(2006.01)
G21C 13/00	(2006.01)
F25D 3/00	(2006.01)
G01M 3/00	(2006.01)
G01N 25/72	(2006.01)

(52) **U.S. Cl.**
CPC ***G01M 3/002*** (2013.01); ***G01N 25/72*** (2013.01)

(58) **Field of Classification Search**
CPC G01K 17/00; G01K 1/14; G01K 13/00; G01K 15/007; G01K 1/026; G01K 7/04; G21F 5/12; B65D 83/38; G01N 25/72
USPC 374/4, 137, 208, 141, 54; 250/506.1
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,073,961 A *	1/1963	Nachbar	G21F 5/10	250/506.1
3,229,096 A *	1/1966	Bonilla	G21F 5/005	250/507.1
4,437,578 A *	3/1984	Bienek	G21F 5/12	220/288
8,410,946 B2 *	4/2013	Ansari	G01M 3/002	340/605

(Continued)

FOREIGN PATENT DOCUMENTS

EP	1492385 A2 *	12/2004	H05B 3/746
JP	2002202400 A	7/2002	

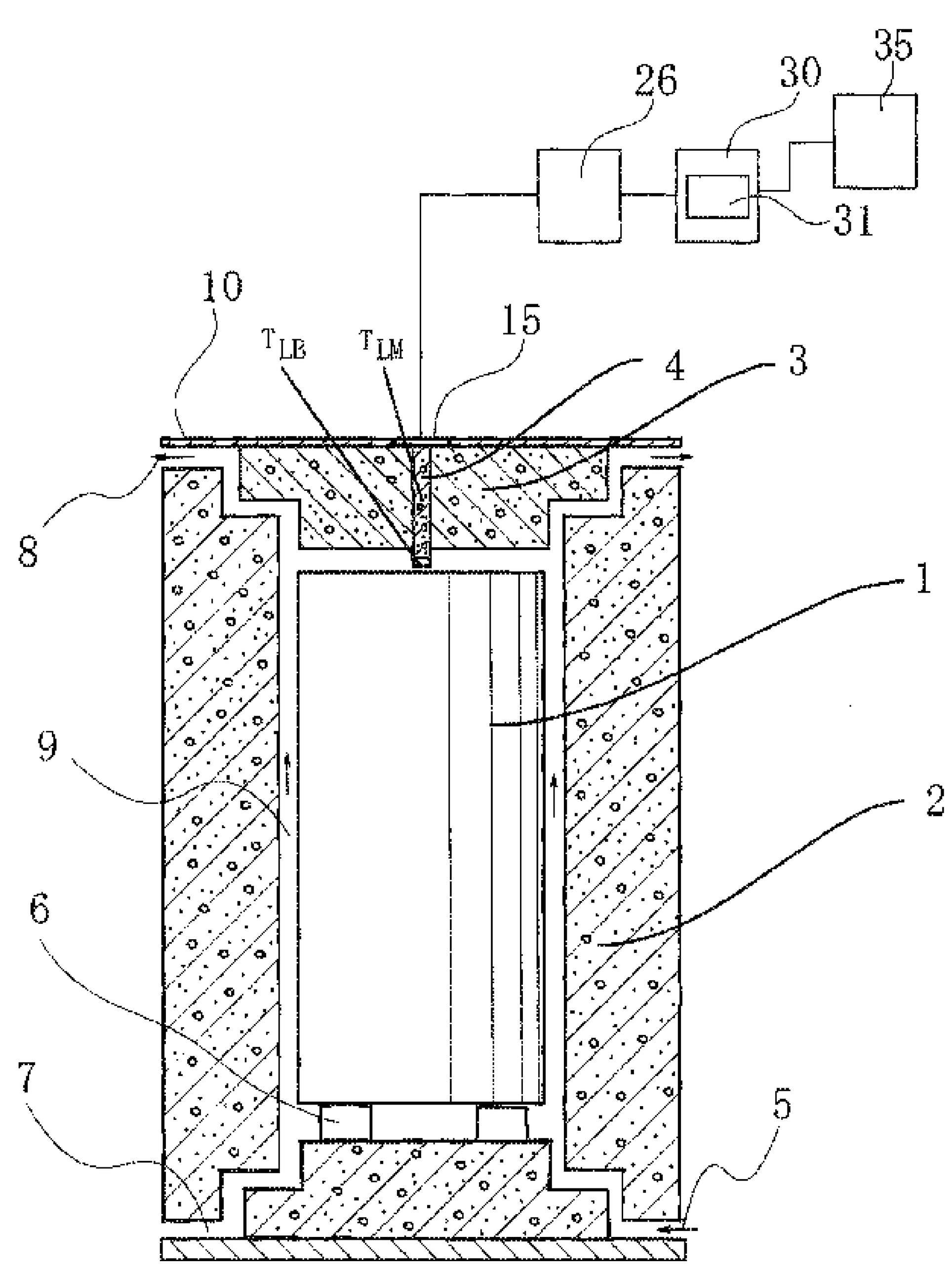
(Continued)

Primary Examiner — Gail Kaplan Verbitsky
(74) *Attorney, Agent, or Firm* — The Webb Law Firm

(57) **ABSTRACT**

A method for detecting gas leakage from a radioactive material sealed container includes measuring a temperature at a top portion of a metallic sealed container, a temperature at a bottom portion of a lid portion of a concrete-made storage container facing the top portion of the metallic sealed container, or a temperature of a member existing between the bottom portion of the lid portion and the top portion of the metallic sealed container. An inner temperature of the lid portion of the concrete-made storage container is also measured. Presence of leakage of inactive gas is estimated by comparing the temperatures.

15 Claims, 21 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

2005/0145633	A1*	7/2005	Goto	A47J 36/06 220/573.4
2011/0215936	A1*	9/2011	Ansari	G01M 3/002 340/584
2015/0059445	A1*	3/2015	Tragsdorf	G21F 5/12 73/49.2
2017/0108396	A1*	4/2017	Takeda	G01M 3/002
2018/0073163	A1*	3/2018	Higashi	C30B 25/12
2018/0130565	A1*	5/2018	Lehnert	G21F 5/012

FOREIGN PATENT DOCUMENTS

JP	2004077124	A	3/2004
JP	2004226385	A	8/2004
JP	2005265443	A	9/2005

* cited by examiner

Fig. 1

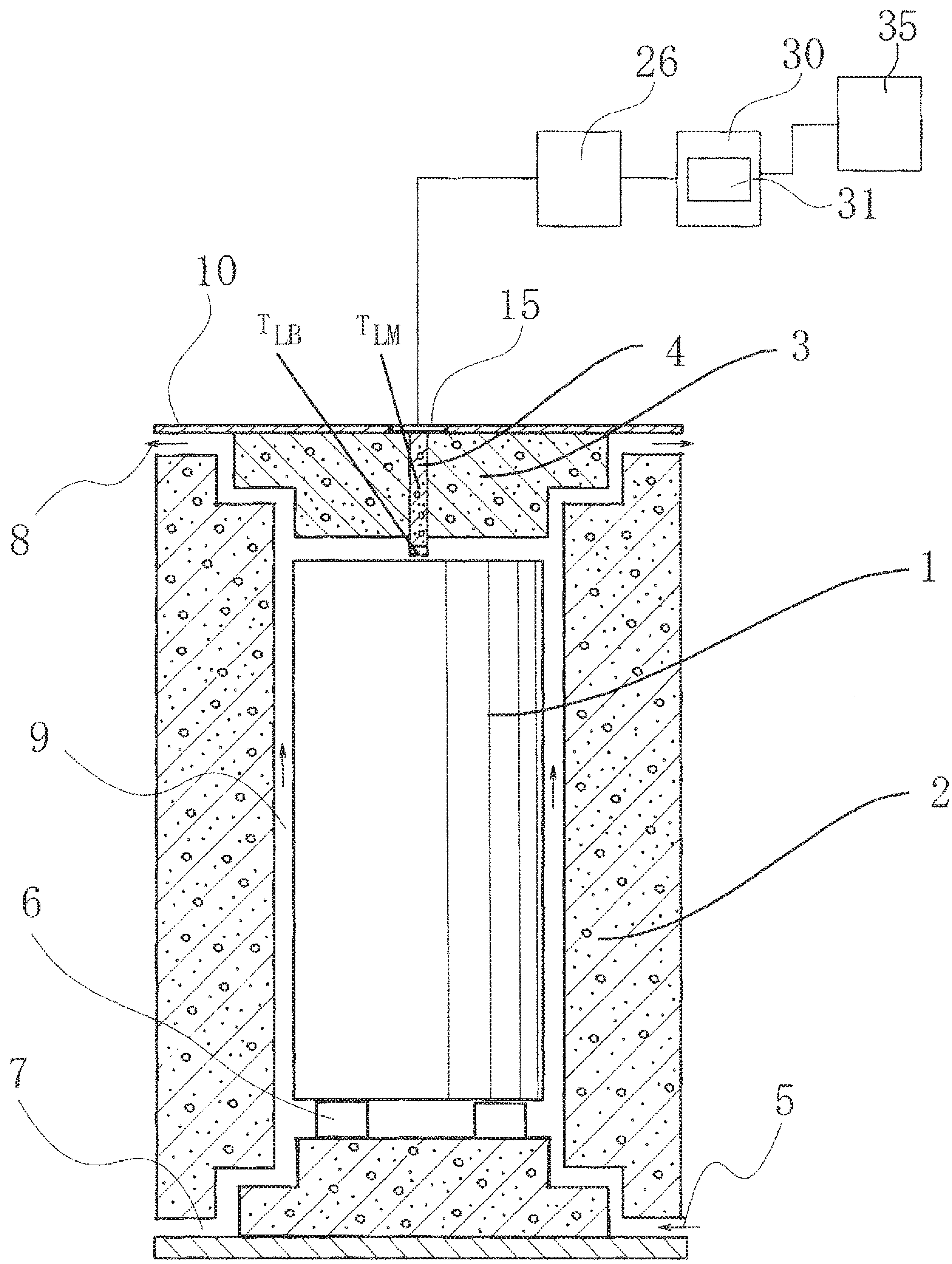


Fig. 2

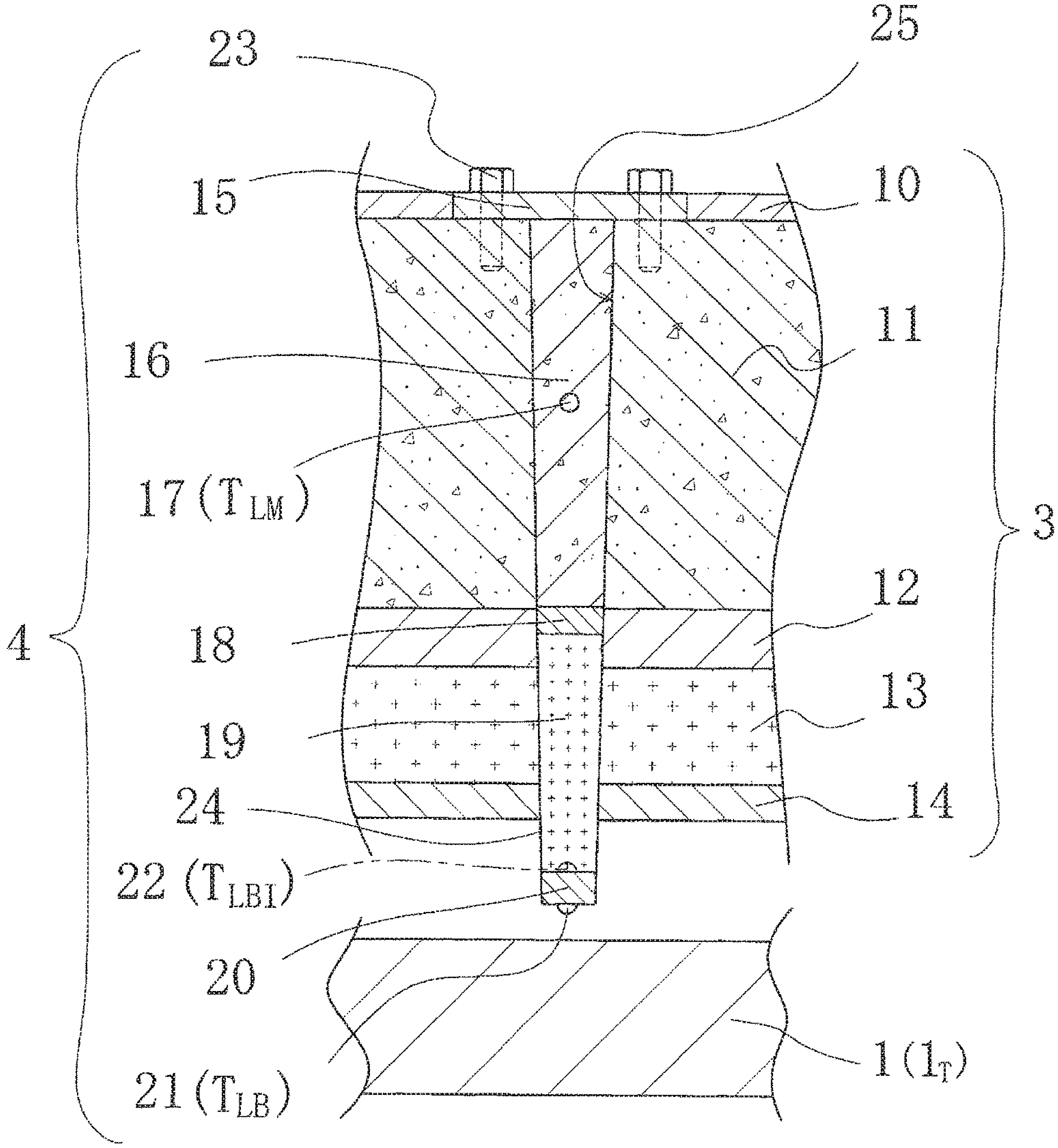


Fig. 3

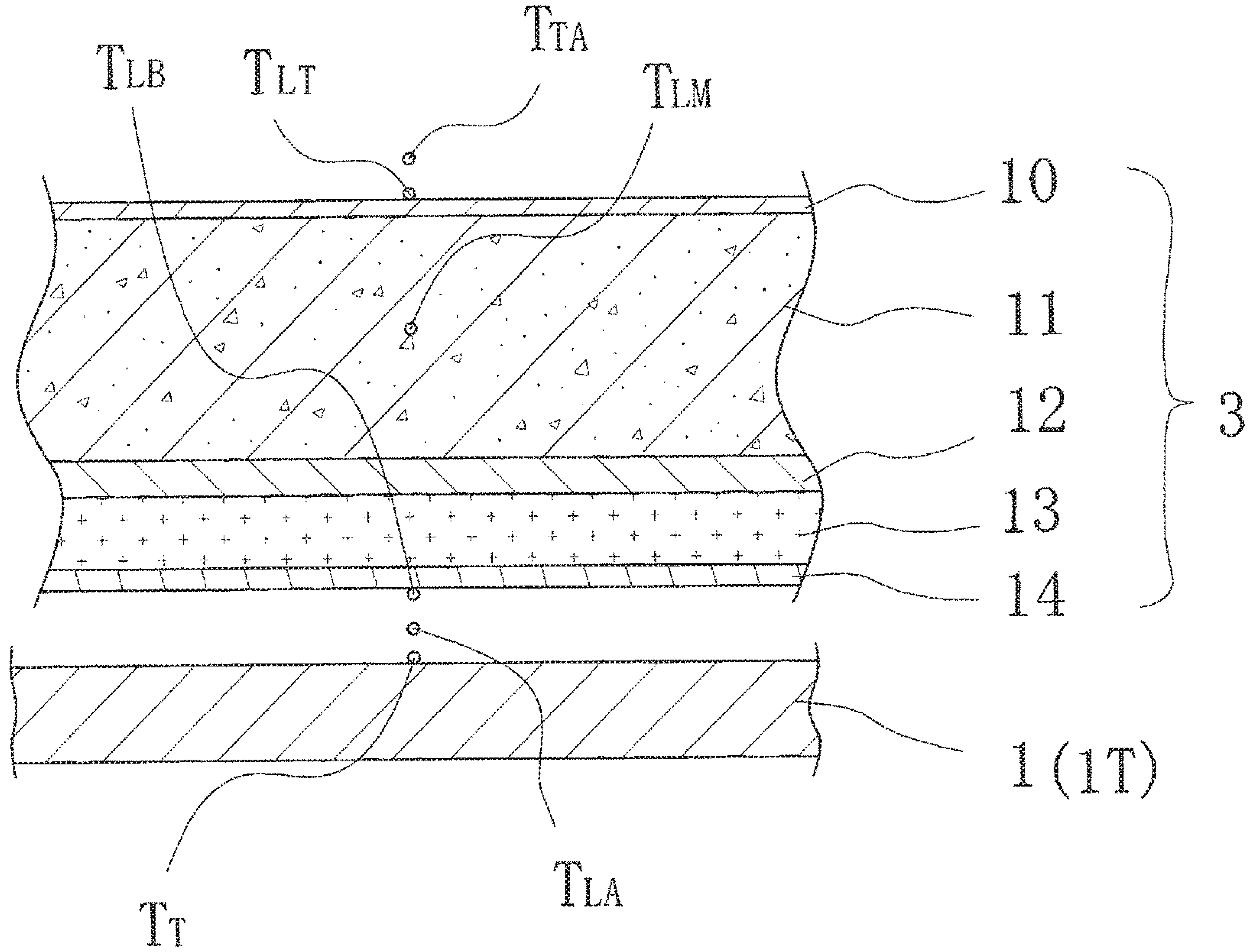


Fig. 4C

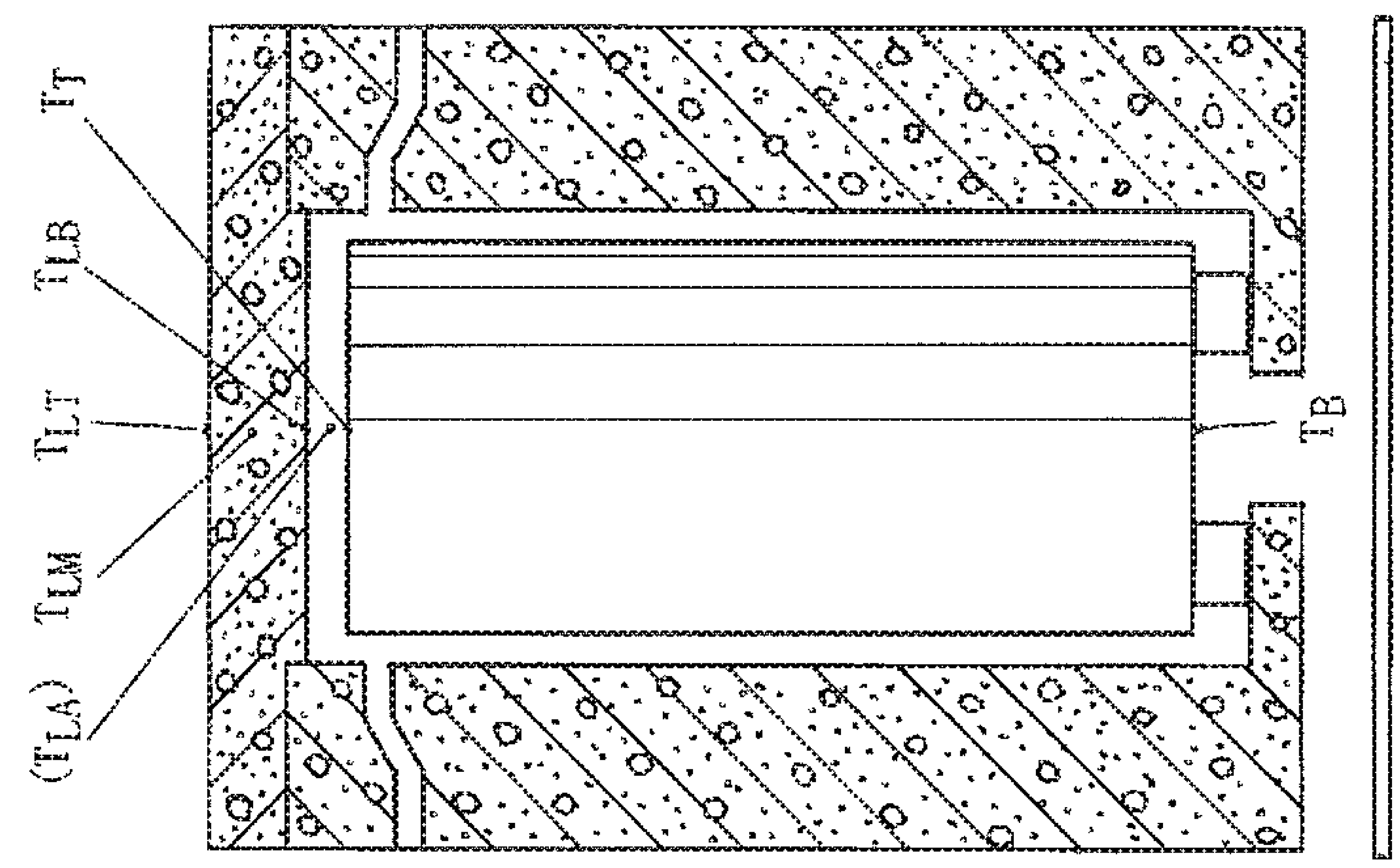


Fig. 4B

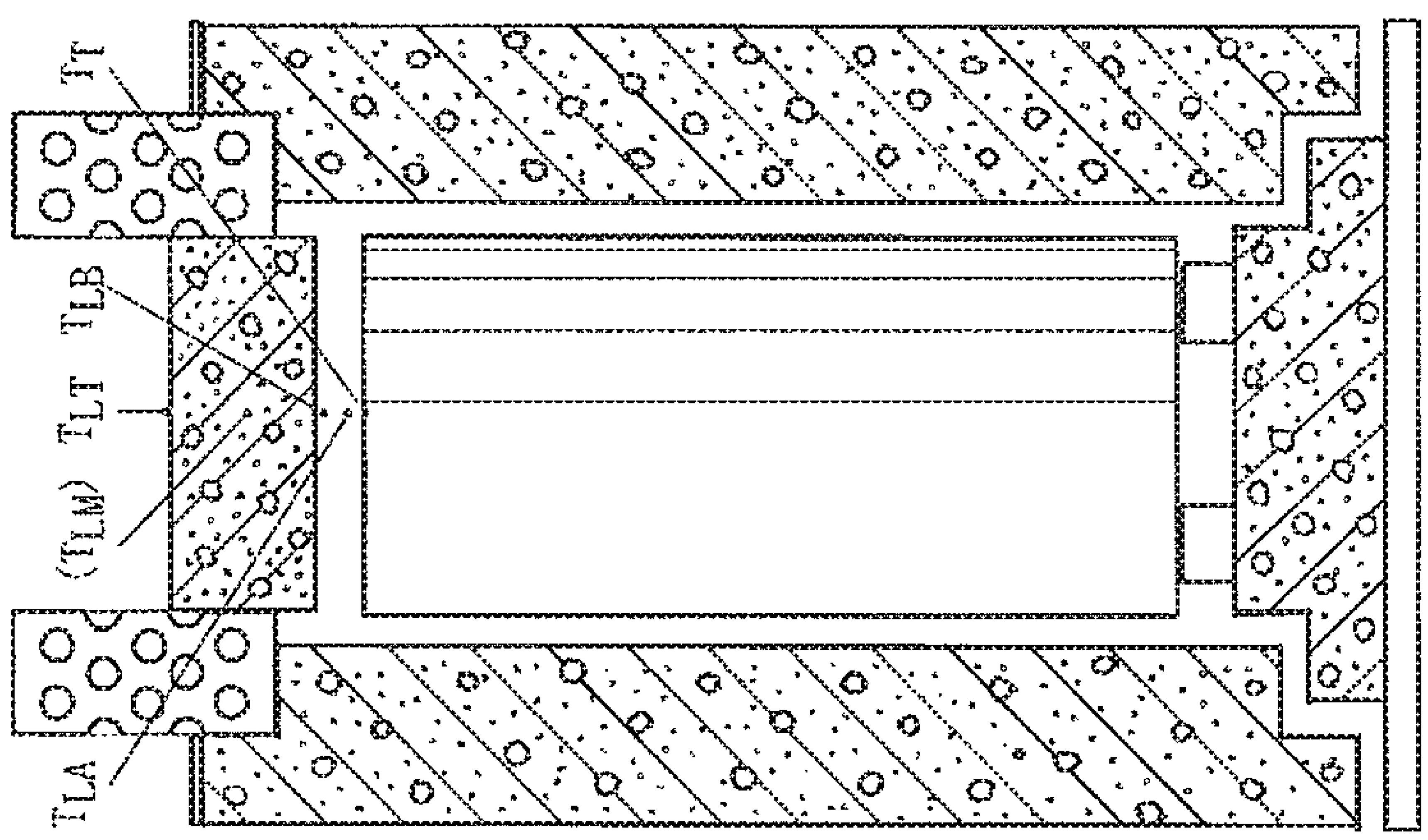


Fig. 4A

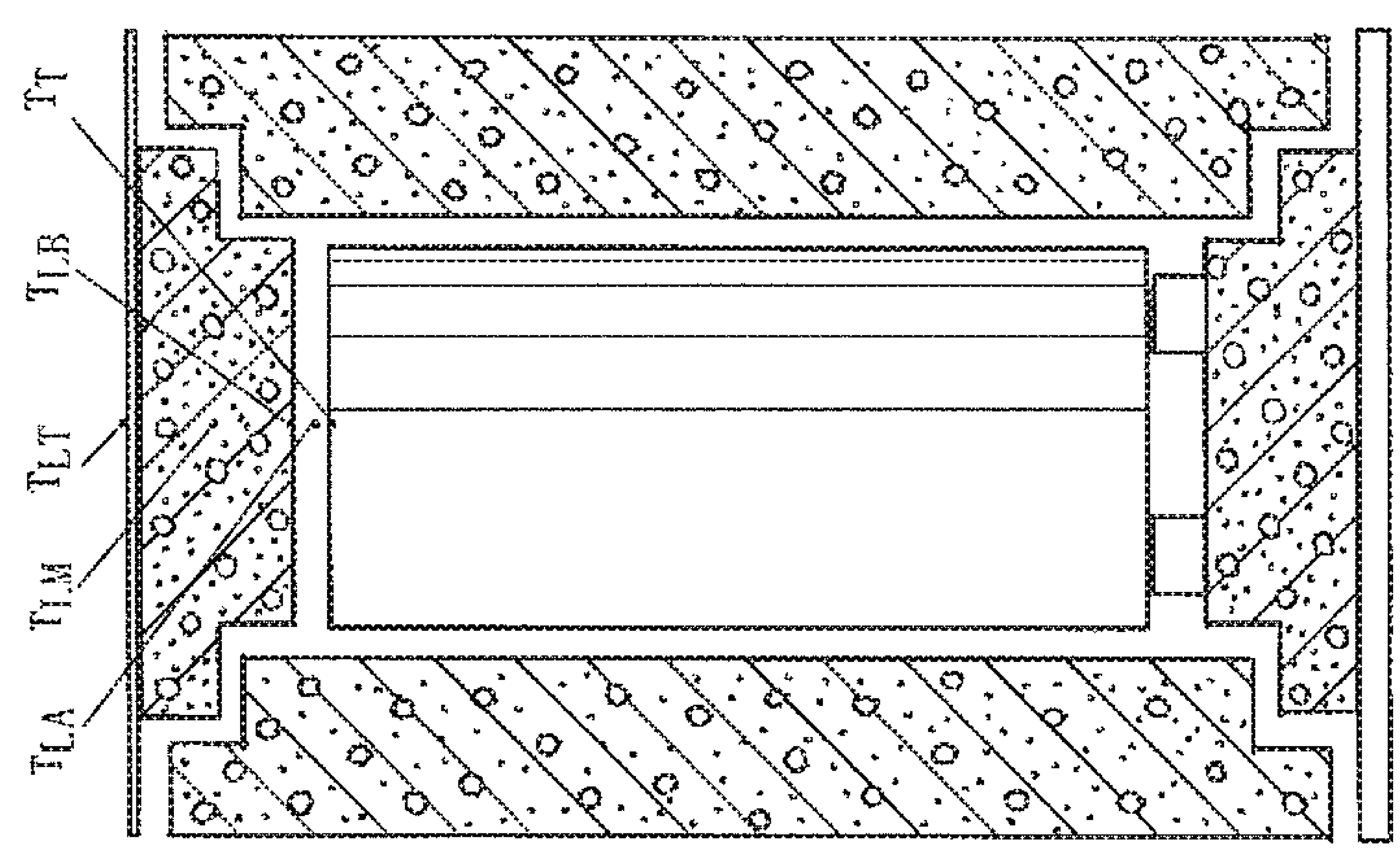
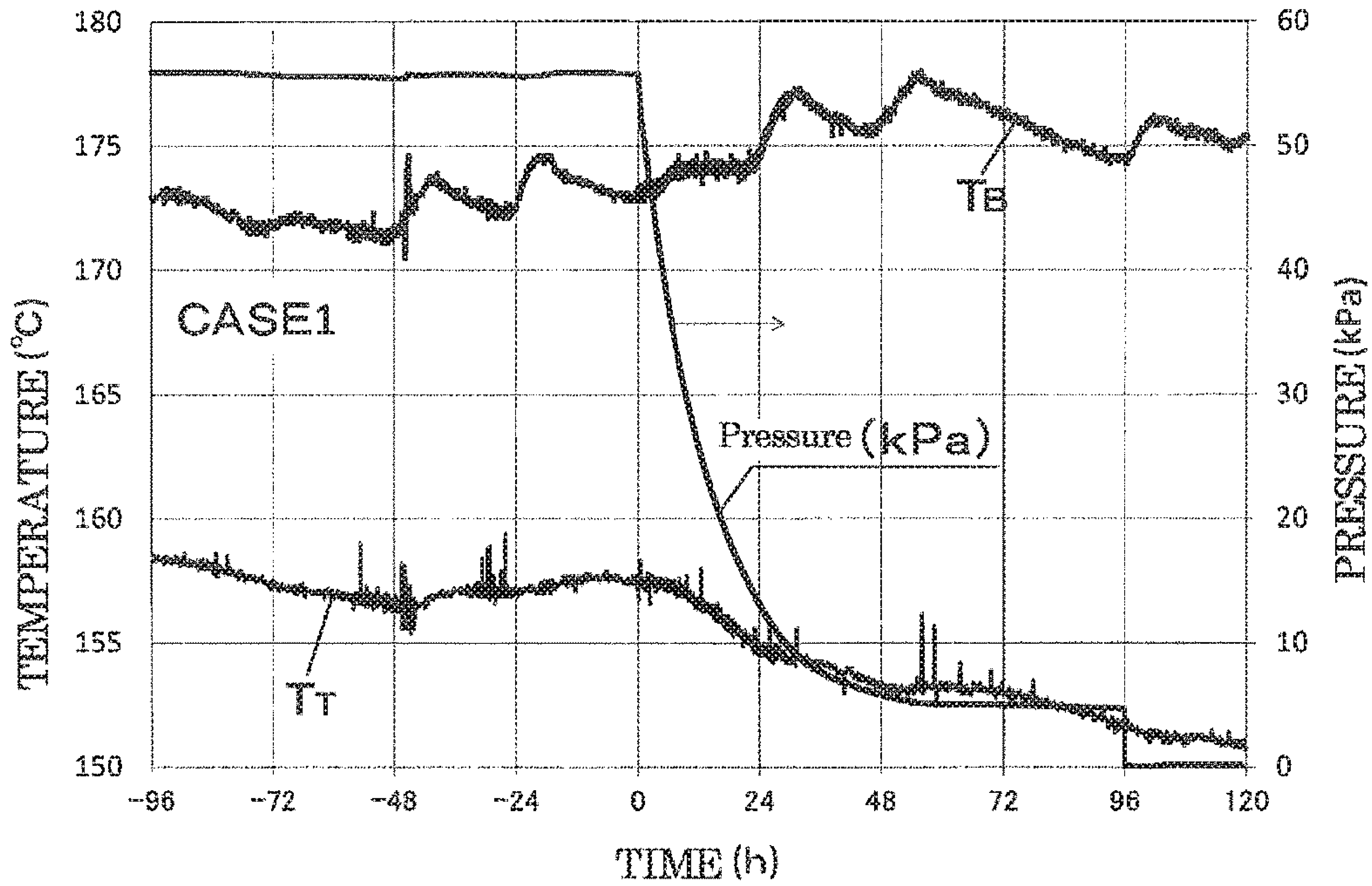
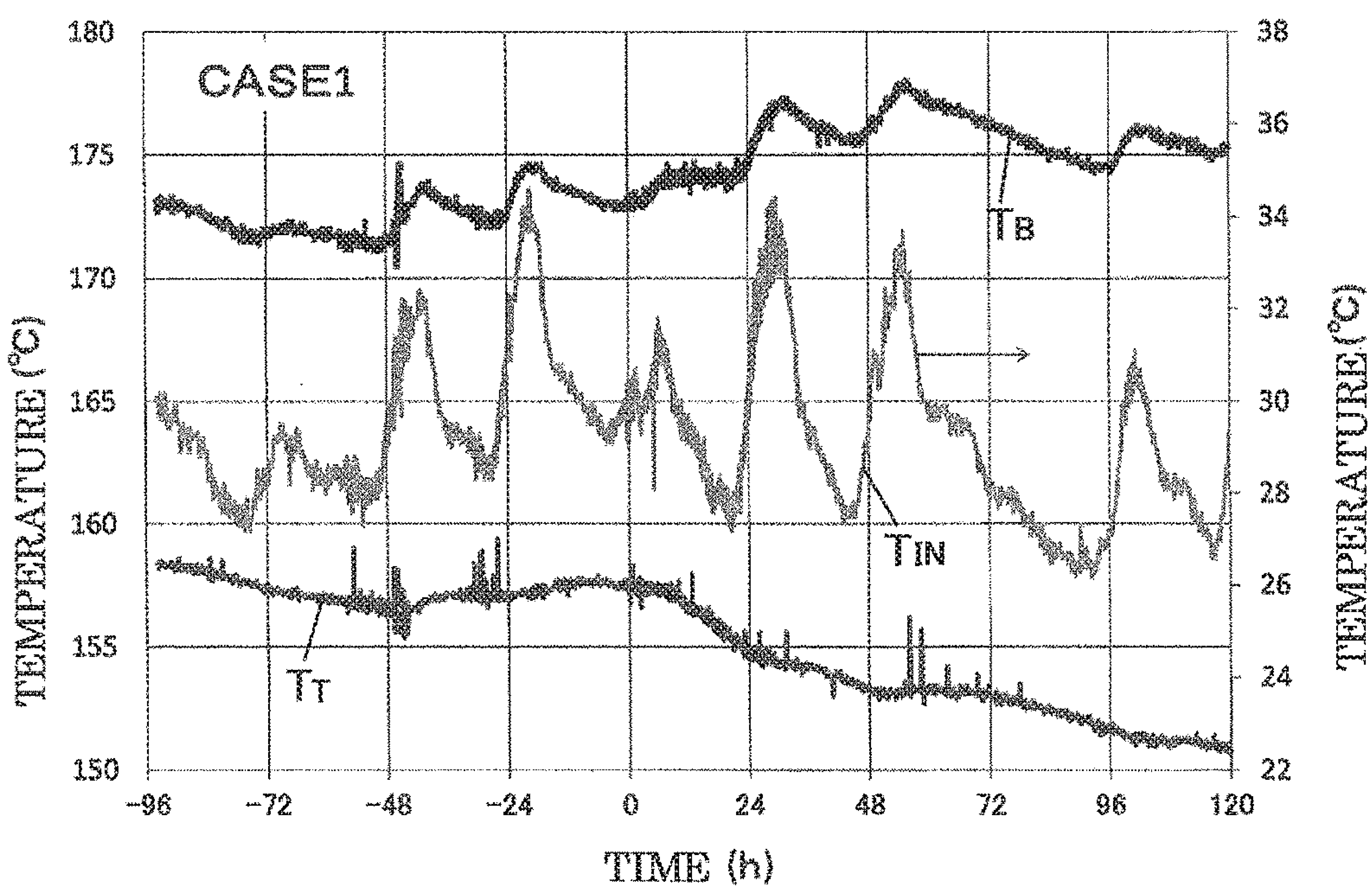


Fig. 5



180
175
170
165
160
155
150
60
50
40
30
20
10
0
CASE1
Pressure (kPa)
TB
TT
TEMPERATURE (°C)
PRESSURE (kPa)
-96
-72
-48
-24
0
24
48
72
96
120
TIME (h)

Fig. 6



180
175
170
165
160
155
150
38
36
34
32
30
28
26
24
22
CASE1
TB
TIN
TT
TEMPERATURE (°C)
TEMPERATURE (°C)
-96
-72
-48
-24
0
24
48
72
96
120
TIME (h)

Fig. 7

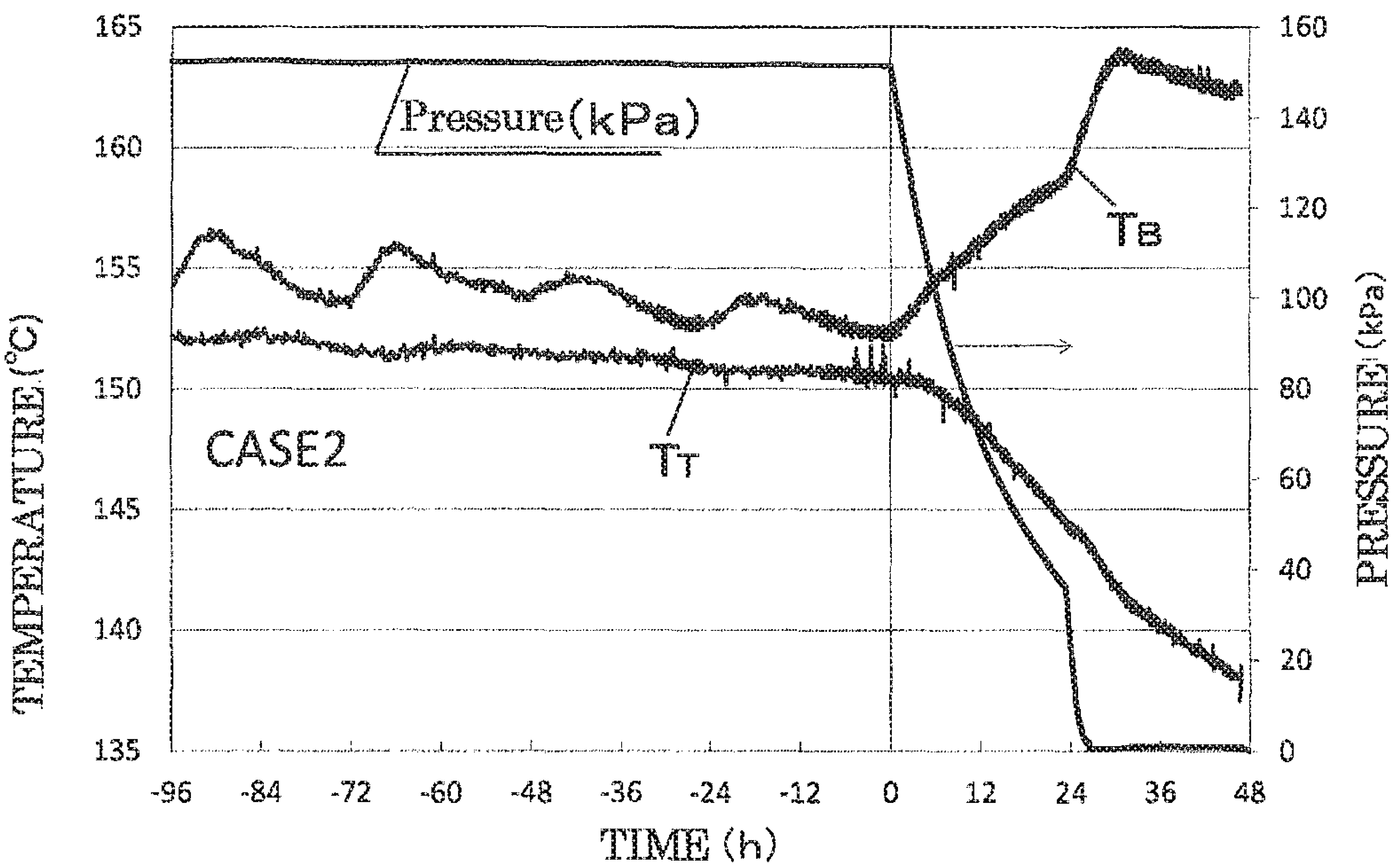

165
160
155
150
145
140
135
160
140
120
100
80
60
40
20
0
Pressure(kPa)
TB
TT
CASE2
TEMPERATURE (°C)
PRESSURE (kPa)
-96
-84
-72
-60
-48
-36
-24
-12
0
12
24
36
48
TIME (h)

Fig. 8

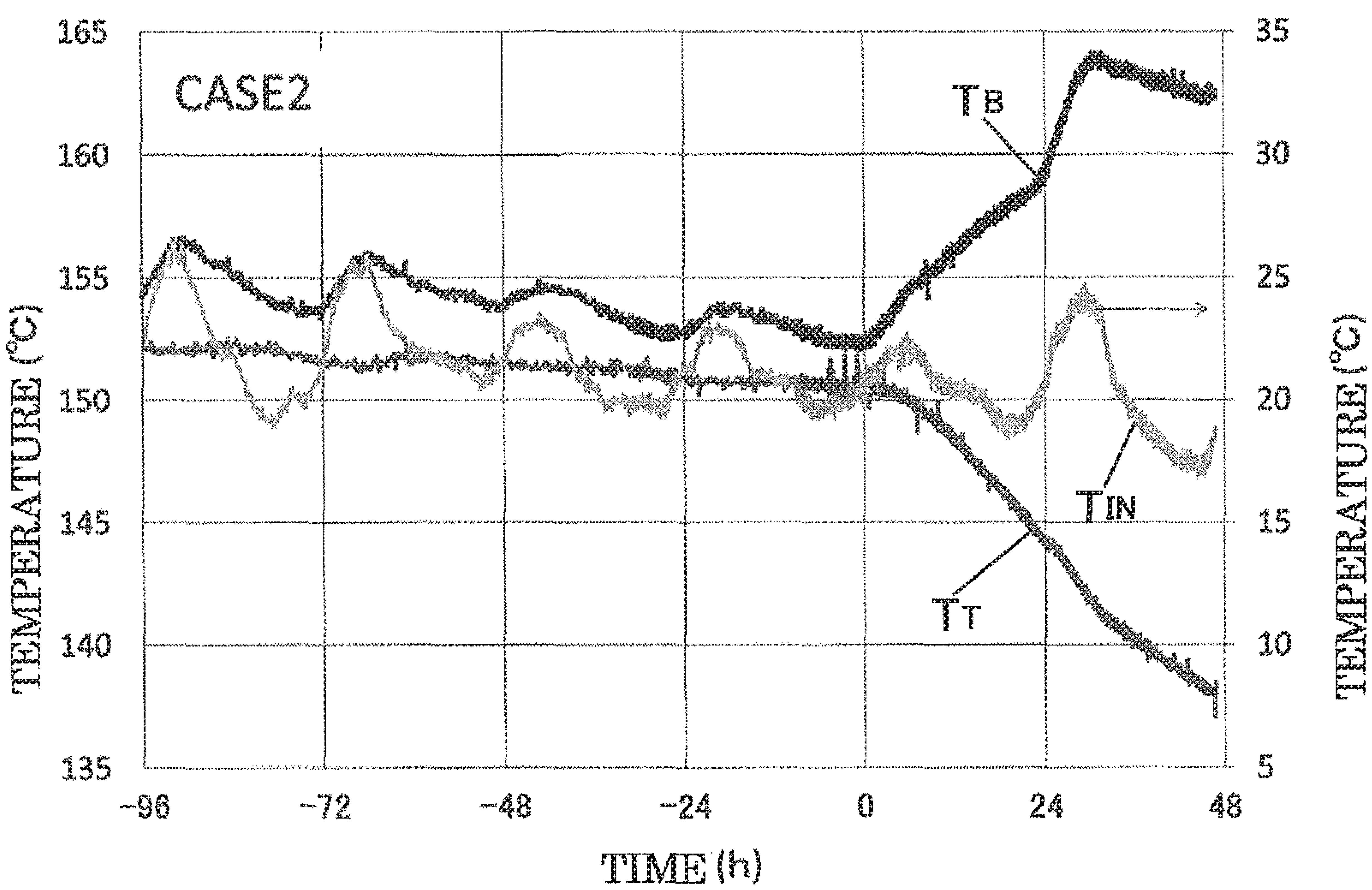

165
160
155
150
145
140
135
35
30
25
20
15
10
5
CASE2
TB
TIN
TT
TEMPERATURE (°C)
TEMPERATURE (°C)
−96
−72
−48
−24
0
24
48
TIME (h)

Fig. 9

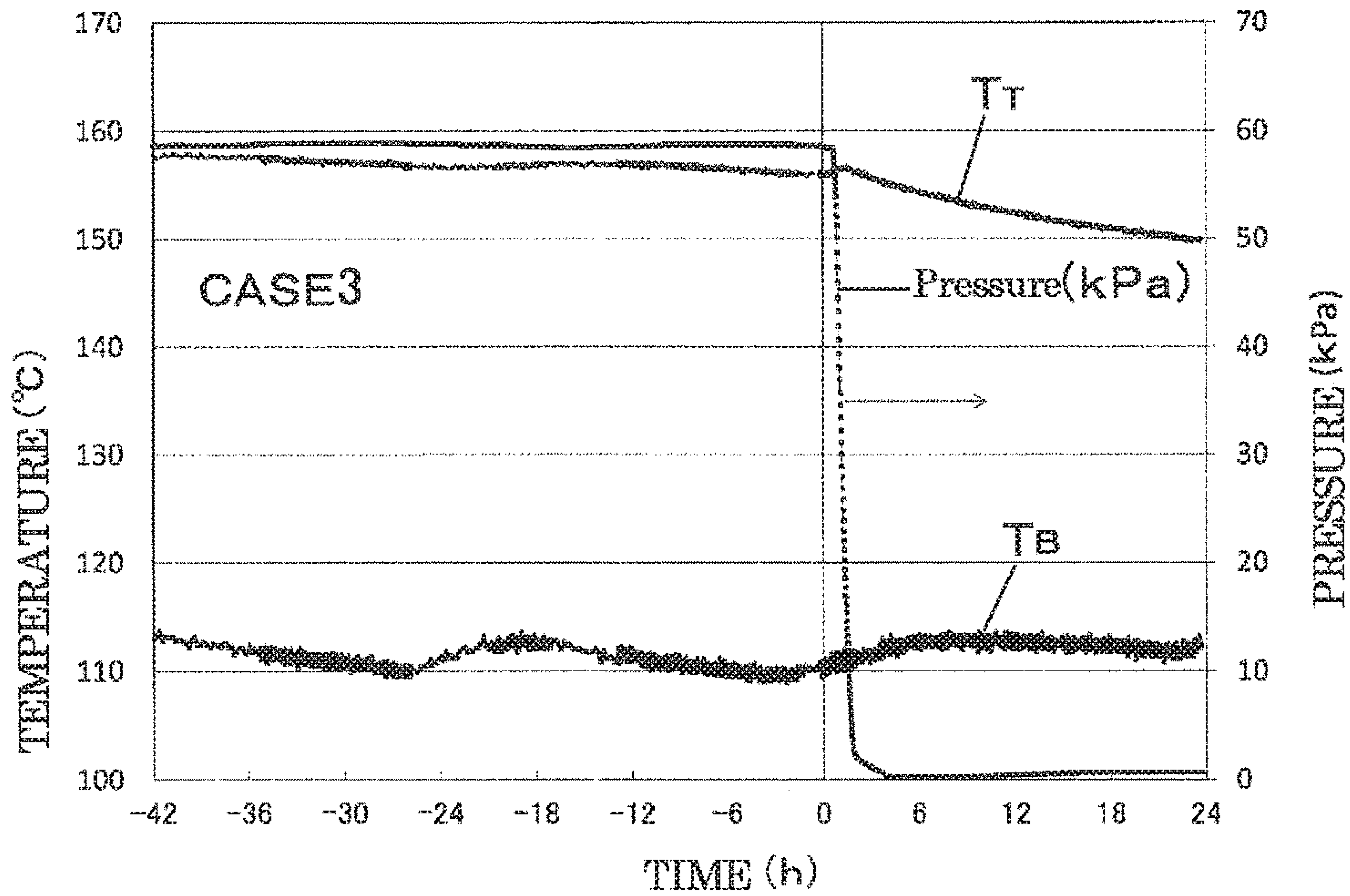

170
160
150
140
130
120
110
100
70
60
50
40
30
20
10
0
-42
-36
-30
-24
-18
-12
-6
0
6
12
18
24
CASE3
TT
TB
Pressure(kPa)
TEMPERATURE (°C)
PRESSURE (kPa)
TIME (h)

Fig. 10

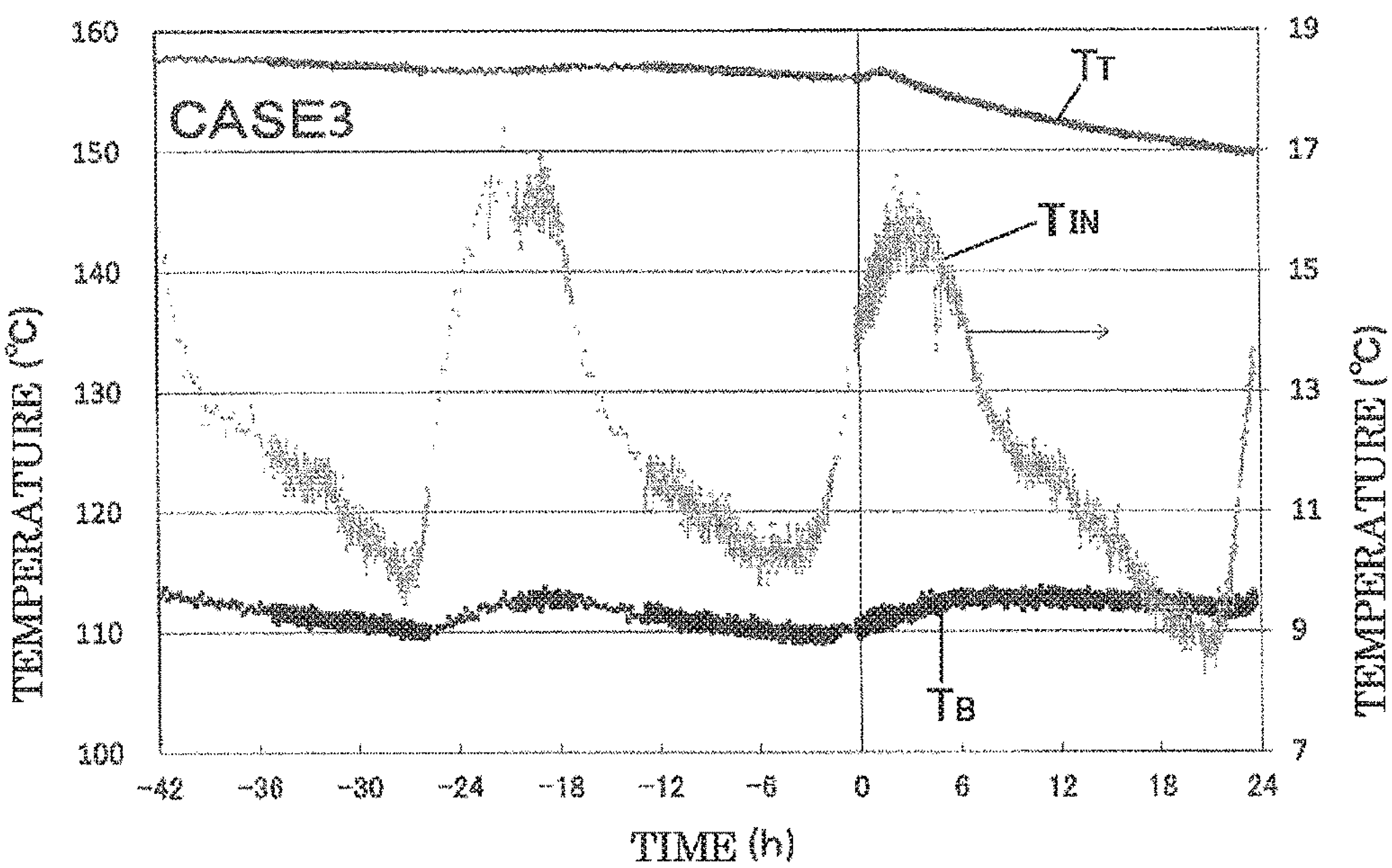

160
150
140
130
120
110
100
19
17
15
13
11
9
7
-42
-36
-30
-24
-18
-12
-6
0
6
12
18
24
CASE3
TT
TIN
TB
TEMPERATURE (°C)
TEMPERATURE (°C)
TIME (h)

Fig. 11

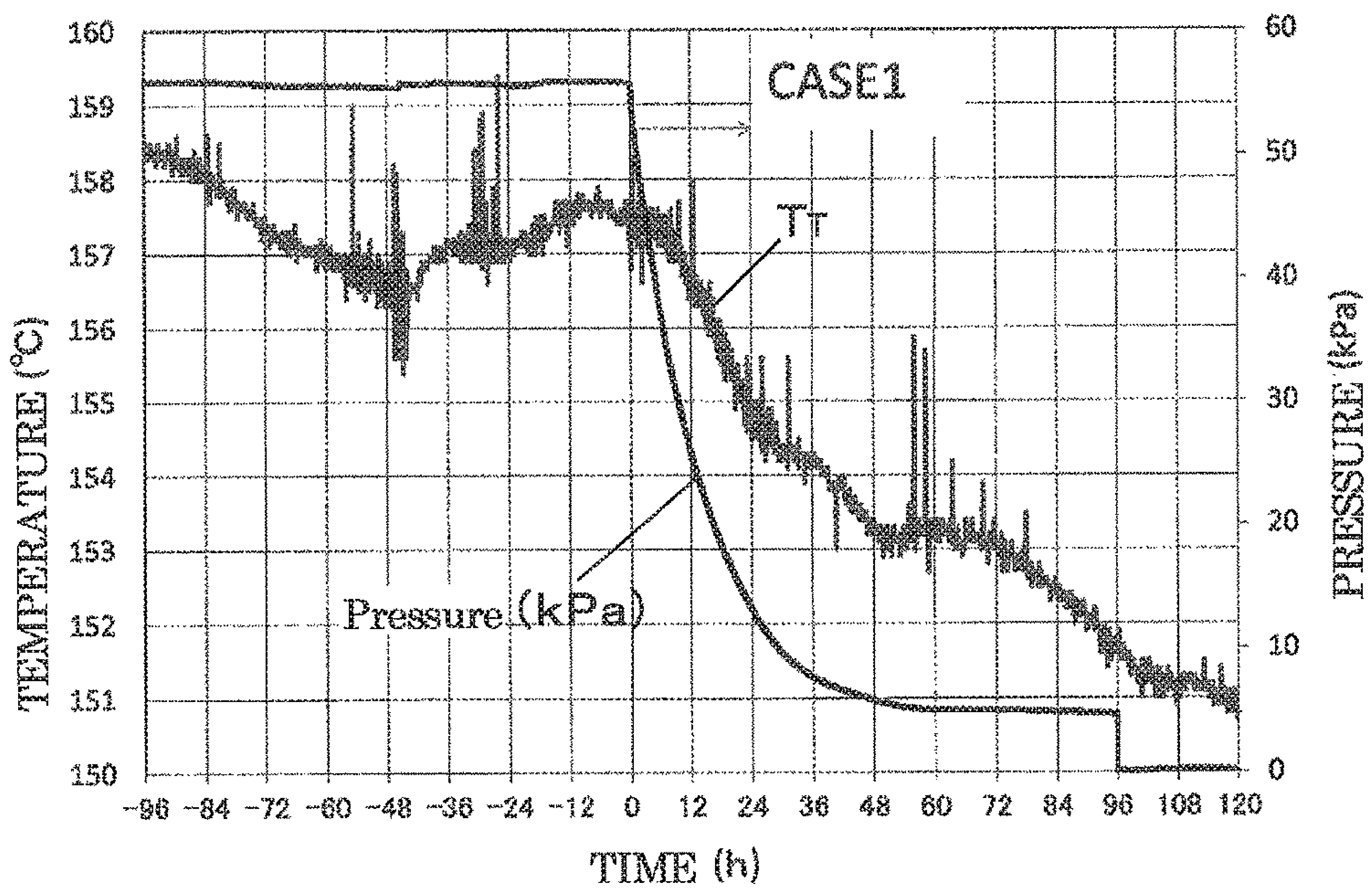

CASE1
T_T
Pressure (kPa)
TEMPERATURE (°C)
PRESSURE (kPa)
TIME (h)
160
159
158
157
156
155
154
153
152
151
150
60
50
40
30
20
10
0
-96 -84 -72 -60 -48 -36 -24 -12 0 12 24 36 48 60 72 84 96 108 120

Fig. 12

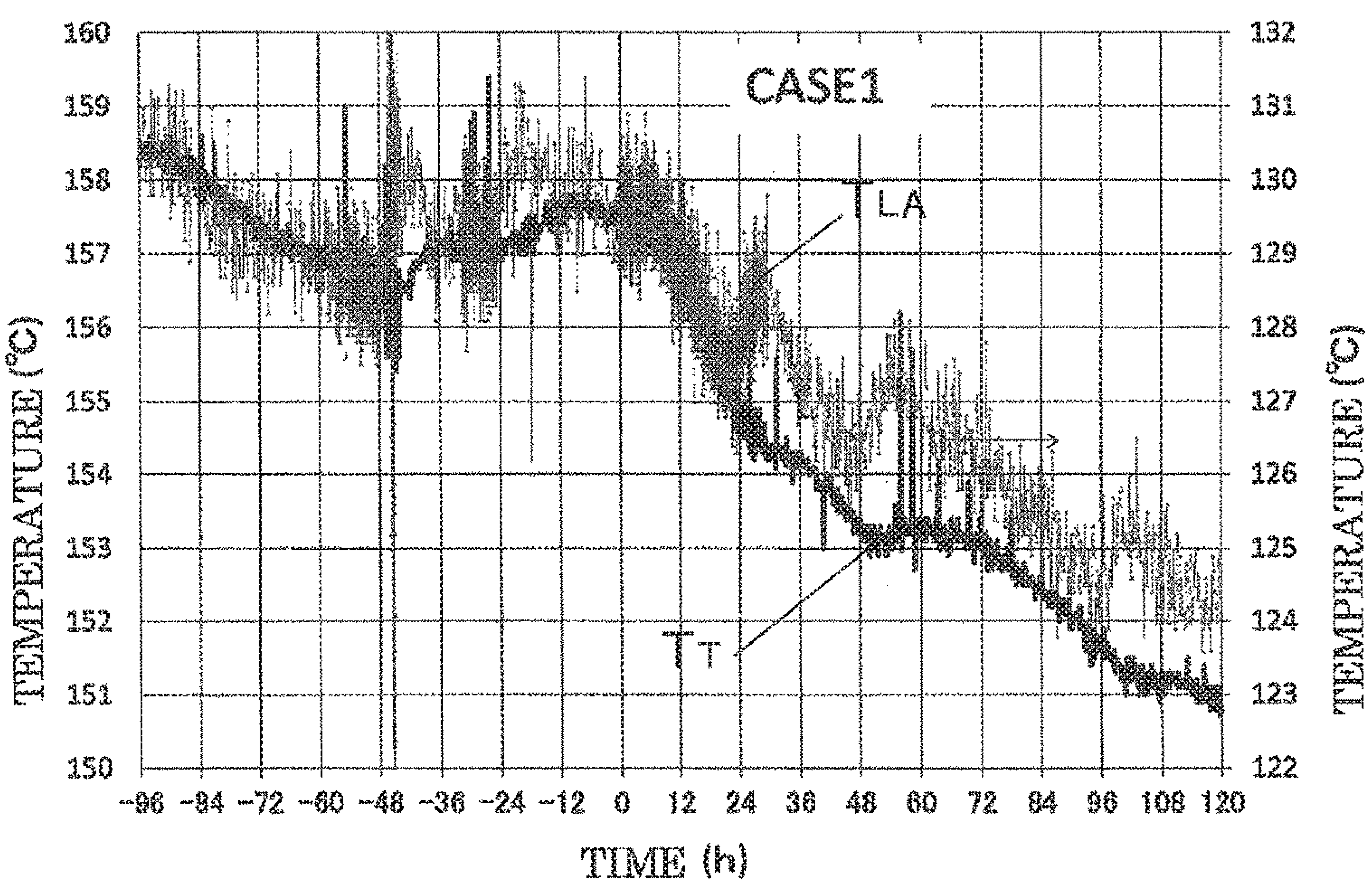

CASE1
T_{LA}
T_T
TEMPERATURE (°C)
TEMPERATURE (°C)
TIME (h)
160
159
158
157
156
155
154
153
152
151
150
132
131
130
129
128
127
126
125
124
123
122
-96 -84 -72 -60 -48 -36 -24 -12 0 12 24 36 48 60 72 84 96 108 120

Fig. 13

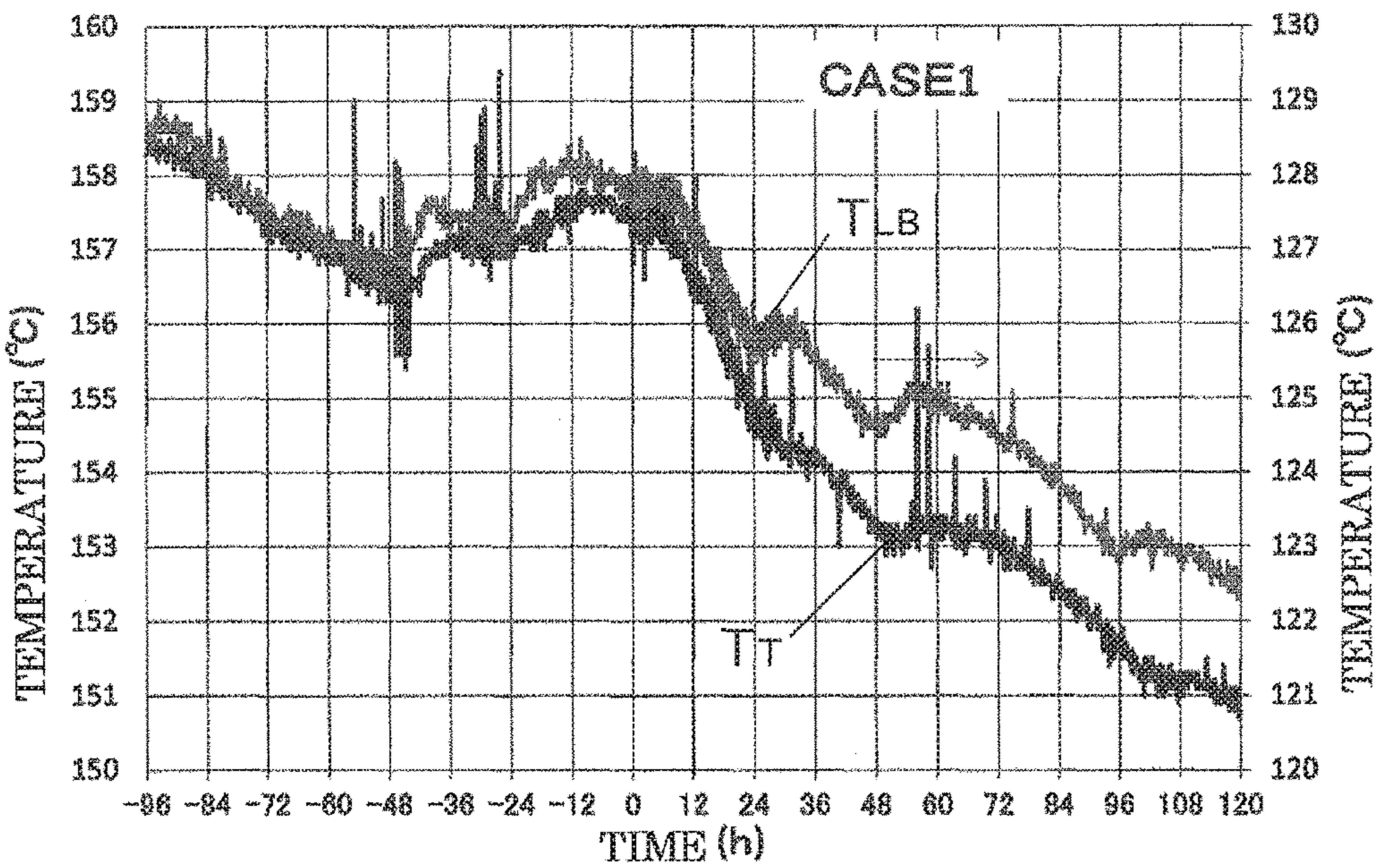

CASE1
T_{LB}
T_T
TEMPERATURE (°C)
TEMPERATURE (°C)
TIME (h)
160
159
158
157
156
155
154
153
152
151
150
130
129
128
127
126
125
124
123
122
121
120
-96 -84 -72 -60 -48 -36 -24 -12 0 12 24 36 48 60 72 84 96 108 120

Fig. 14

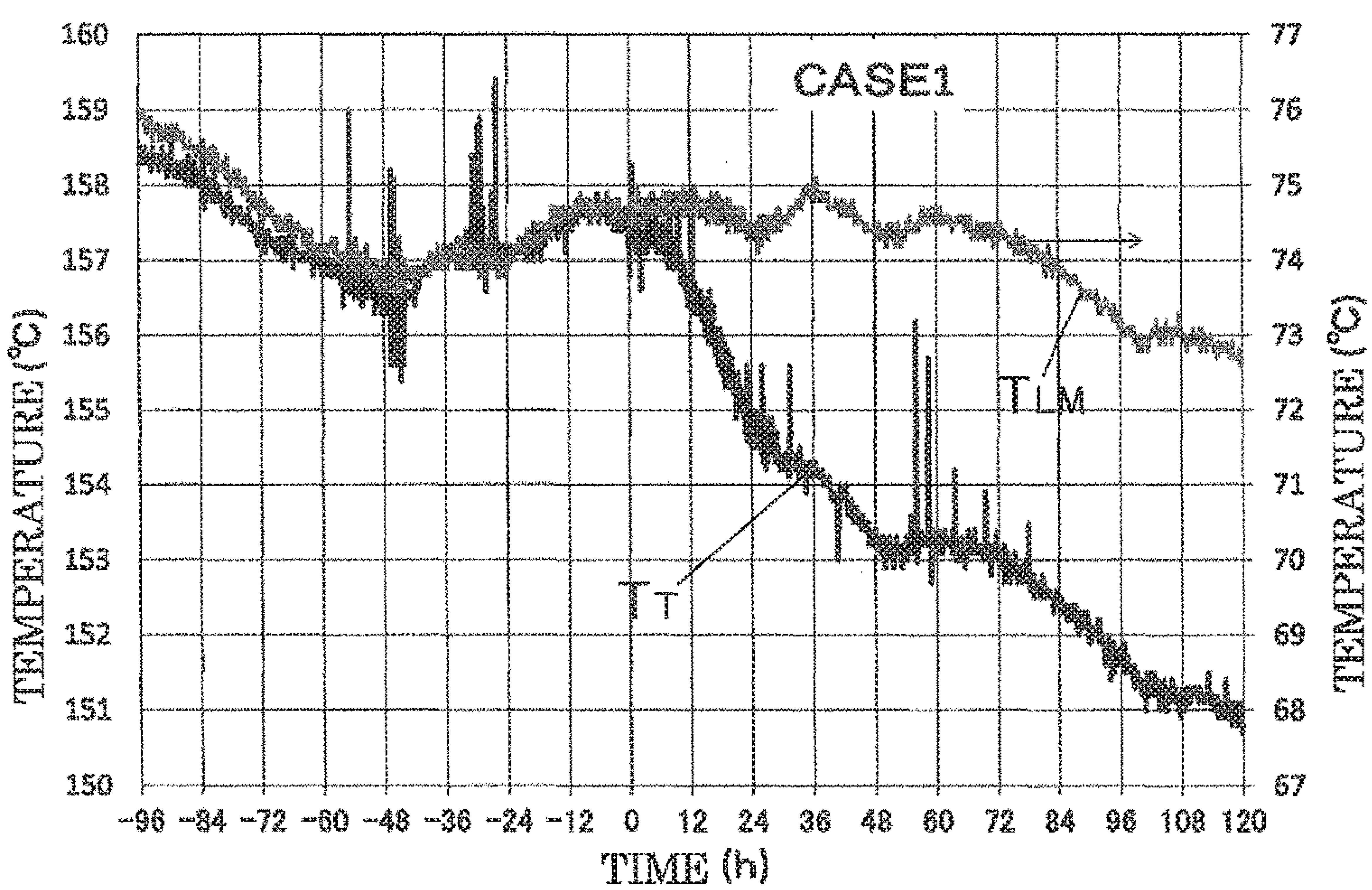

CASE1
T_{LM}
T_T
TEMPERATURE (°C)
TEMPERATURE (°C)
TIME (h)
160
159
158
157
156
155
154
153
152
151
150
77
76
75
74
73
72
71
70
69
68
67
-96 -84 -72 -60 -48 -36 -24 -12 0 12 24 36 48 60 72 84 96 108 120

Fig. 15

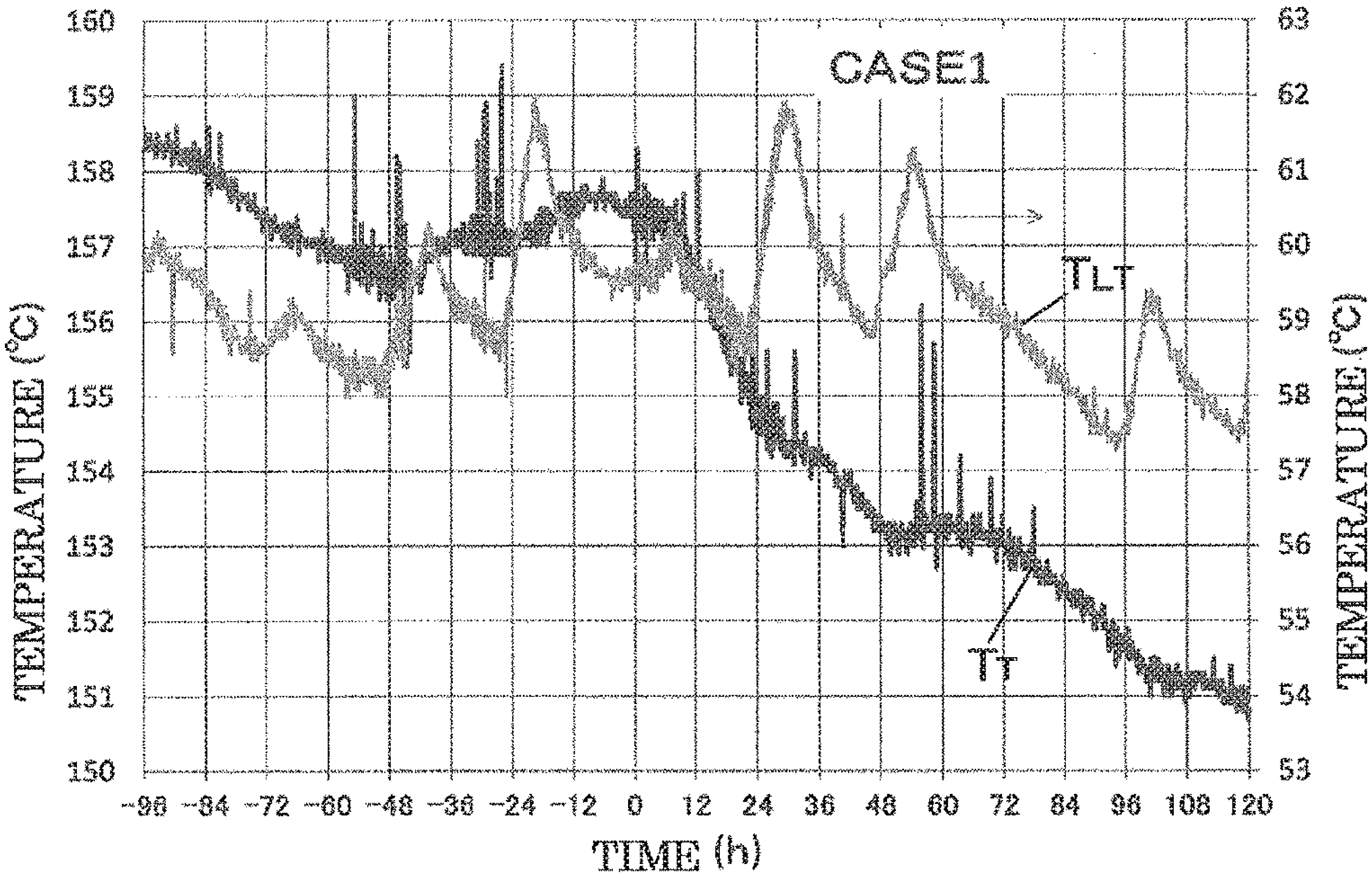

CASE1
TLT
TT
TEMPERATURE (°C)
TIME (h)
160
159
158
157
156
155
154
153
152
151
150
63
62
61
60
59
58
57
56
55
54
53
-96 -84 -72 -60 -48 -36 -24 -12 0 12 24 36 48 60 72 84 96 108 120

Fig. 16

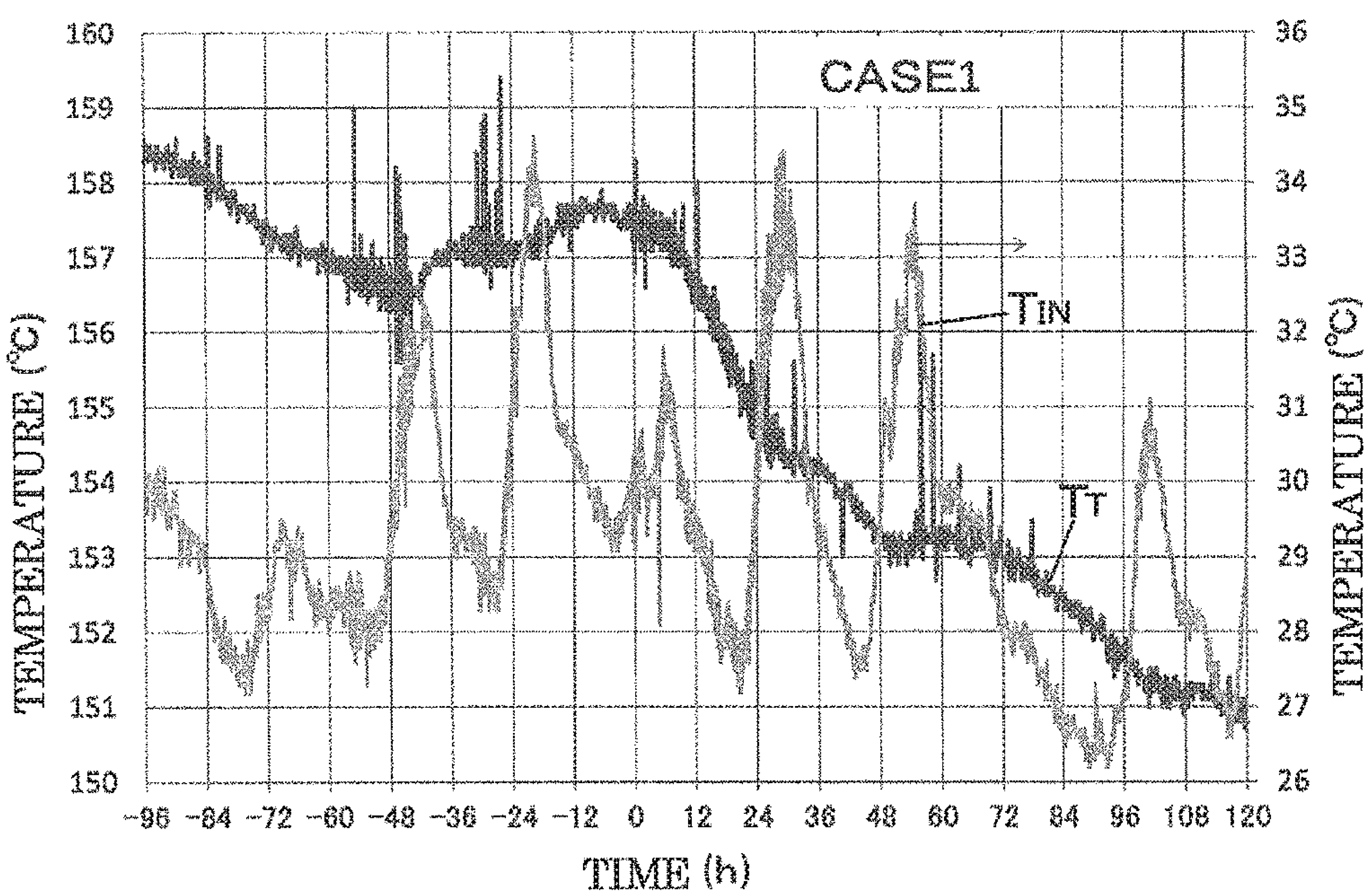

CASE1
TIN
TT
TEMPERATURE (°C)
TIME (h)
160
159
158
157
156
155
154
153
152
151
150
36
35
34
33
32
31
30
29
28
27
26
-96 -84 -72 -60 -48 -36 -24 -12 0 12 24 36 48 60 72 84 96 108 120

Fig. 17

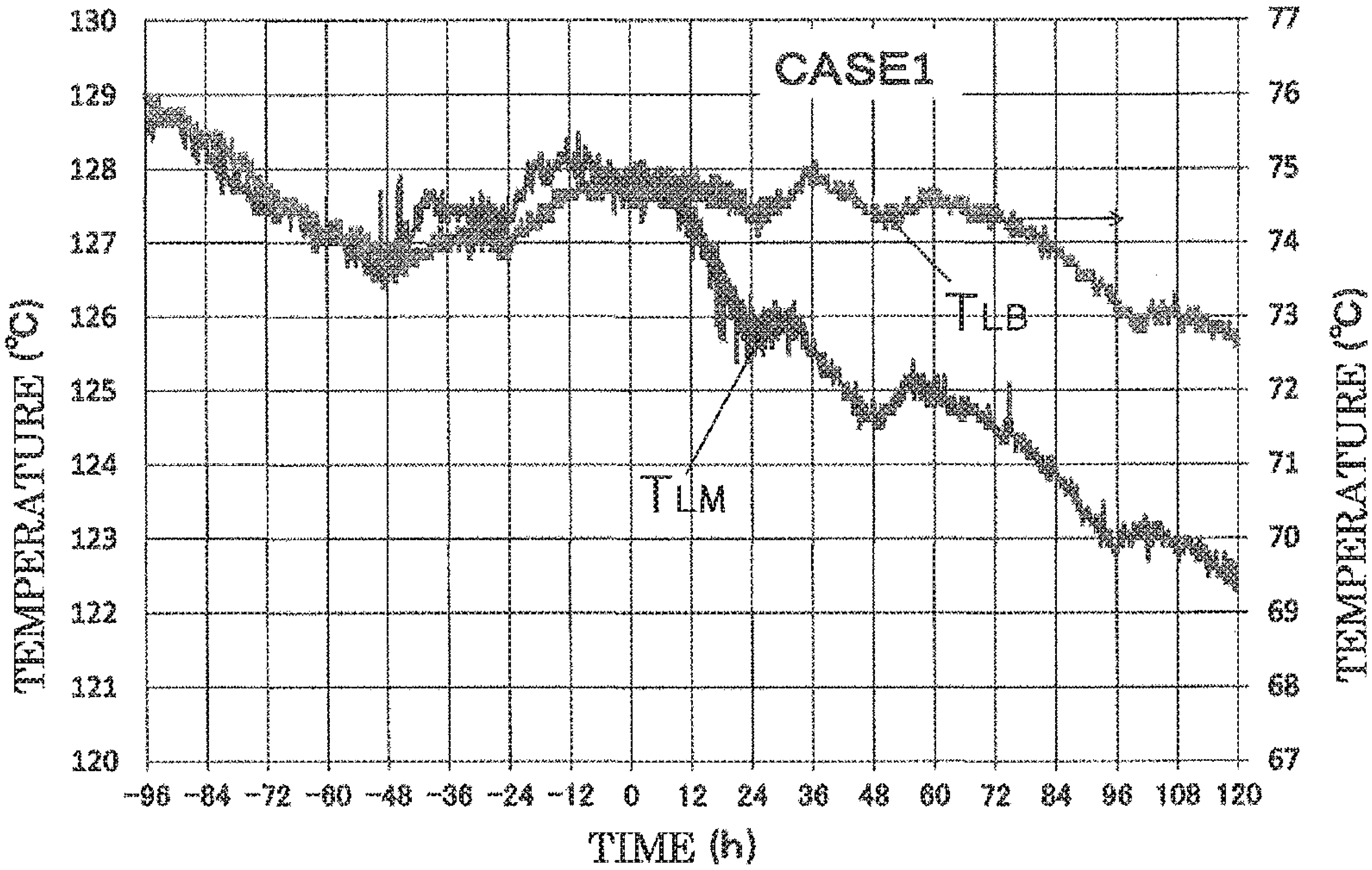

CASE1
TLB
TLM
TEMPERATURE (°C)
TEMPERATURE (°C)
TIME (h)
130
129
128
127
126
125
124
123
122
121
120
77
76
75
74
73
72
71
70
69
68
67
-96 -84 -72 -60 -48 -36 -24 -12 0 12 24 36 48 60 72 84 96 108 120

Fig. 18

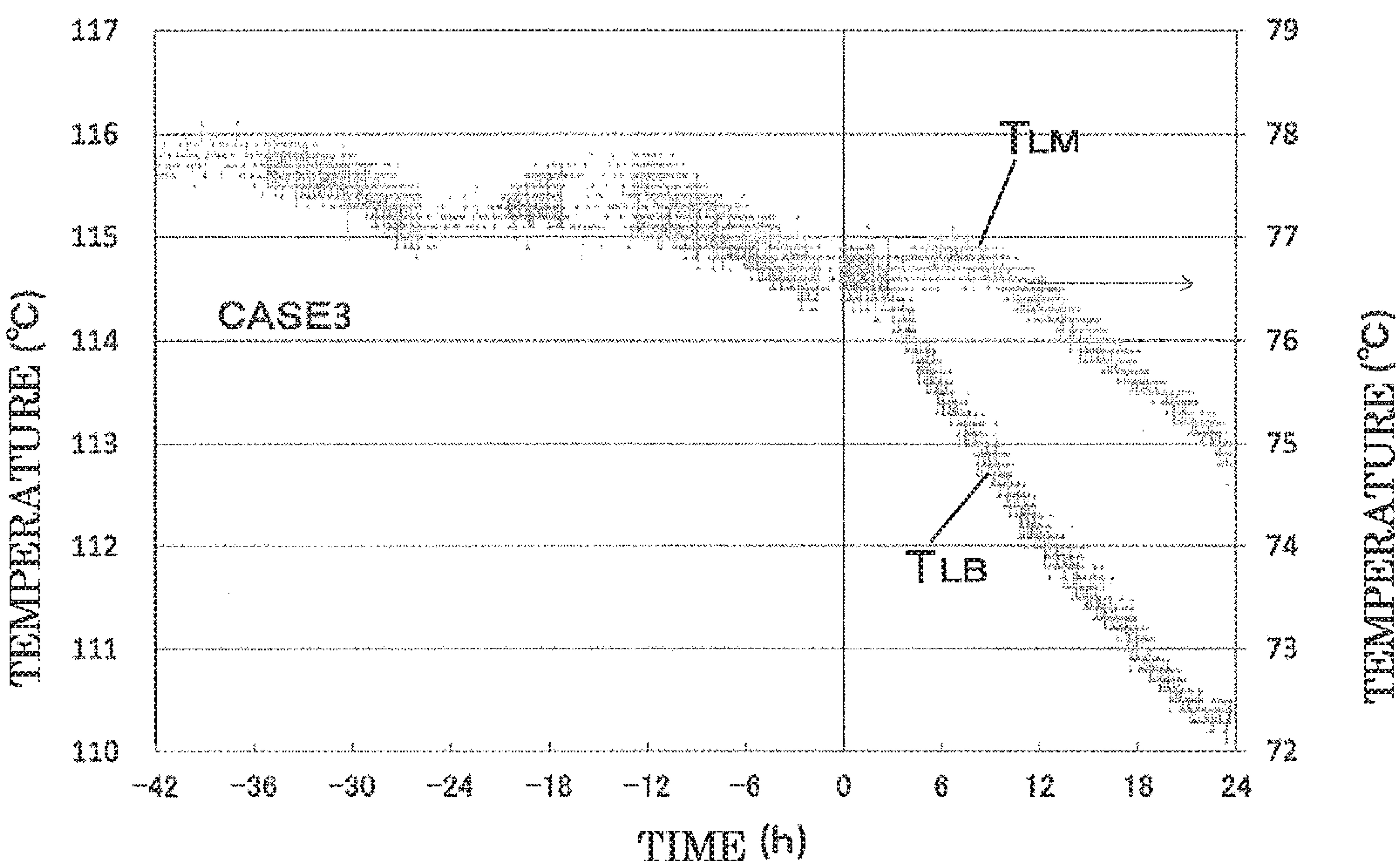

CASE3
TLM
TLB
TEMPERATURE (°C)
TEMPERATURE (°C)
TIME (h)
117
116
115
114
113
112
111
110
79
78
77
76
75
74
73
72
-42 -36 -30 -24 -18 -12 -6 0 6 12 18 24

Fig. 19

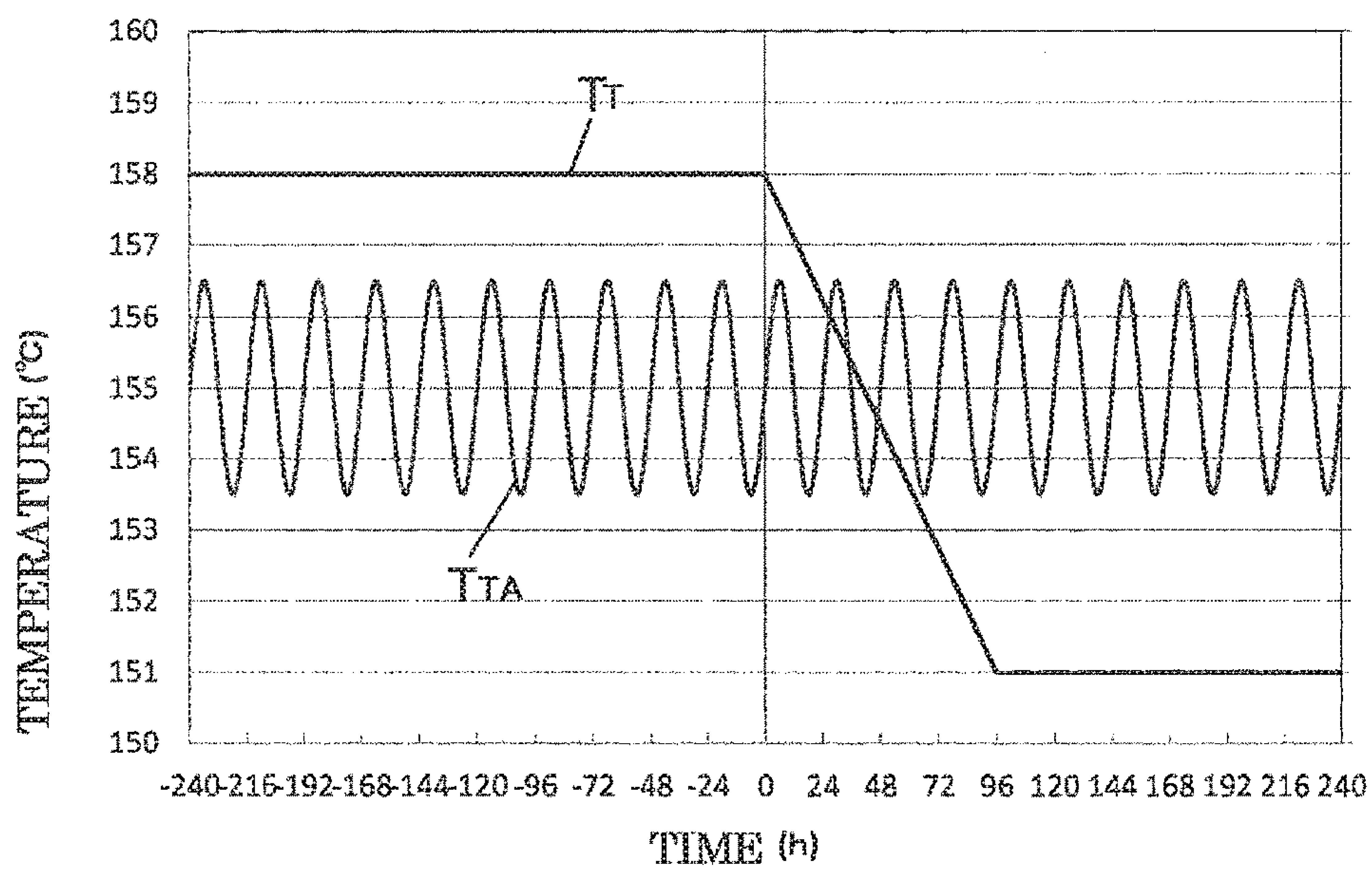

TT
TTA
TEMPERATURE (°C)
160
159
158
157
156
155
154
153
152
151
150
40
38
36
34
32
30
28
26
24
22
20
-240 -216 -192 -168 -144 -120 -96 -72 -48 -24 0 24 48 72 96 120 144 168 192 216 240
TIME (h)

Fig. 20

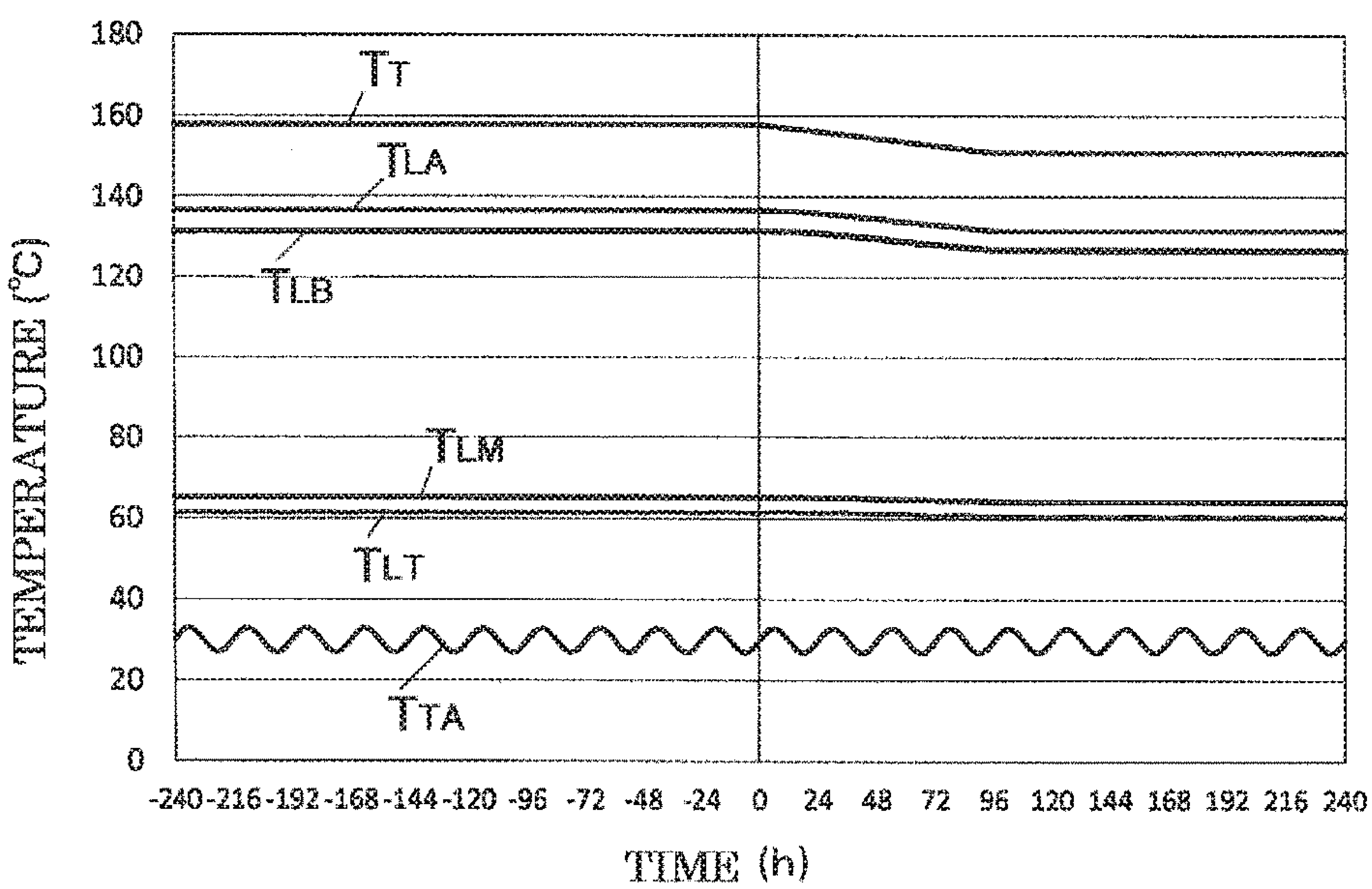

TT
TLA
TLB
TLM
TLT
TTA
TEMPERATURE (°C)
180
160
140
120
100
80
60
40
20
0
-240 -216 -192 -168 -144 -120 -96 -72 -48 -24 0 24 48 72 96 120 144 168 192 216 240
TIME (h)

Fig. 21

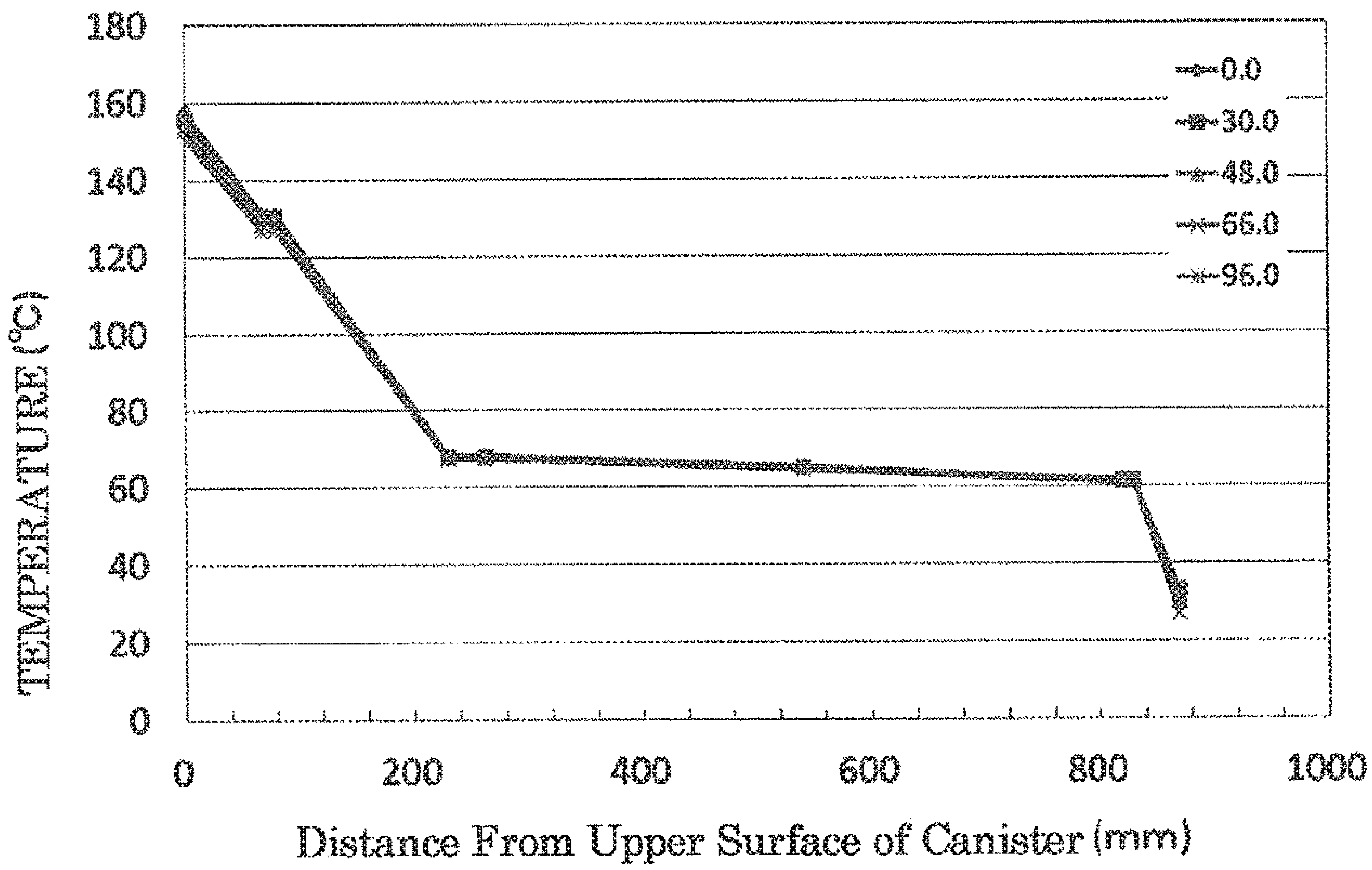

180
160
140
120
100
80
60
40
20
0
0
200
400
600
800
1000
TEMPERATURE (°C)
Distance From Upper Surface of Canister (mm)
0.0
30.0
48.0
66.0
96.0

Fig. 22

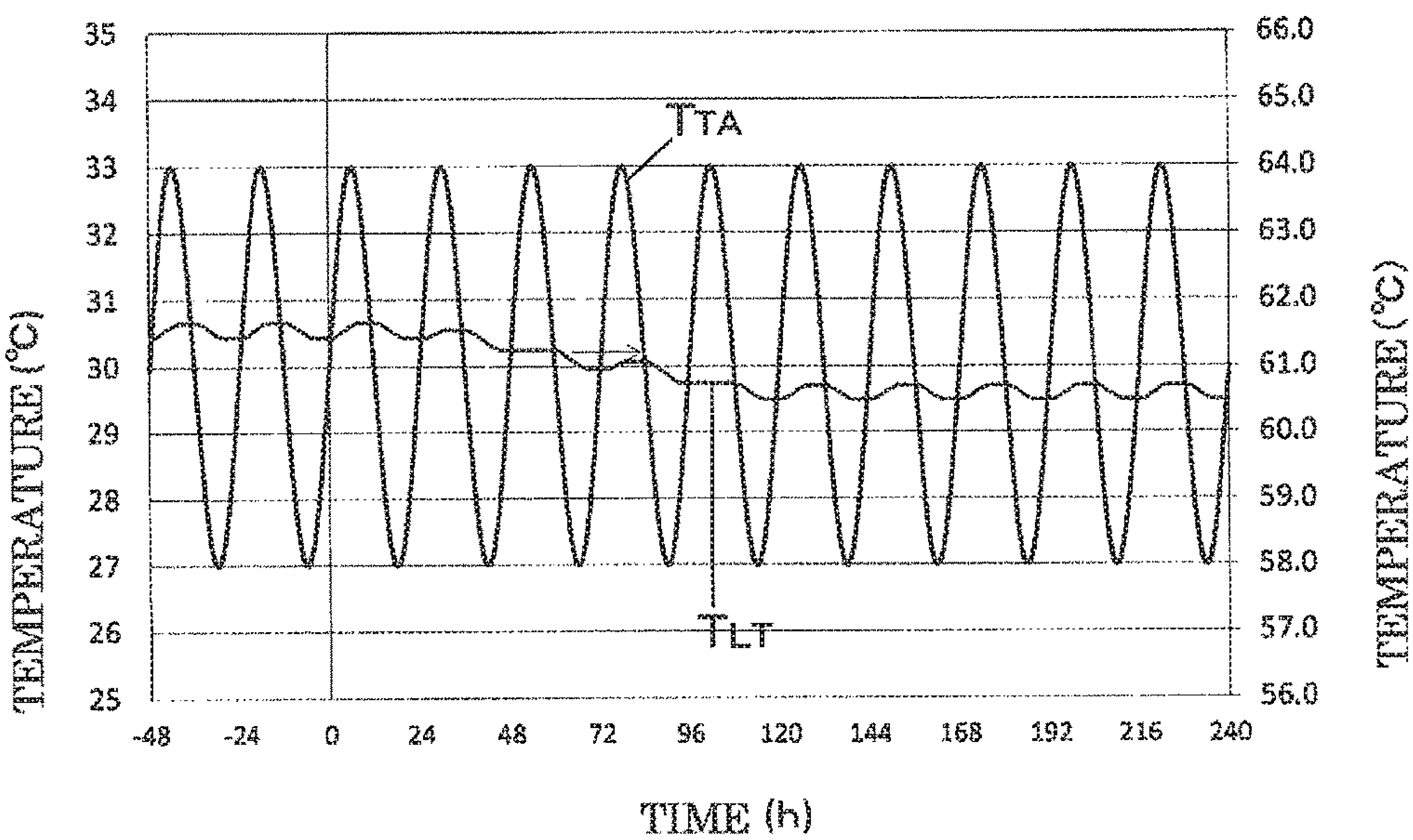
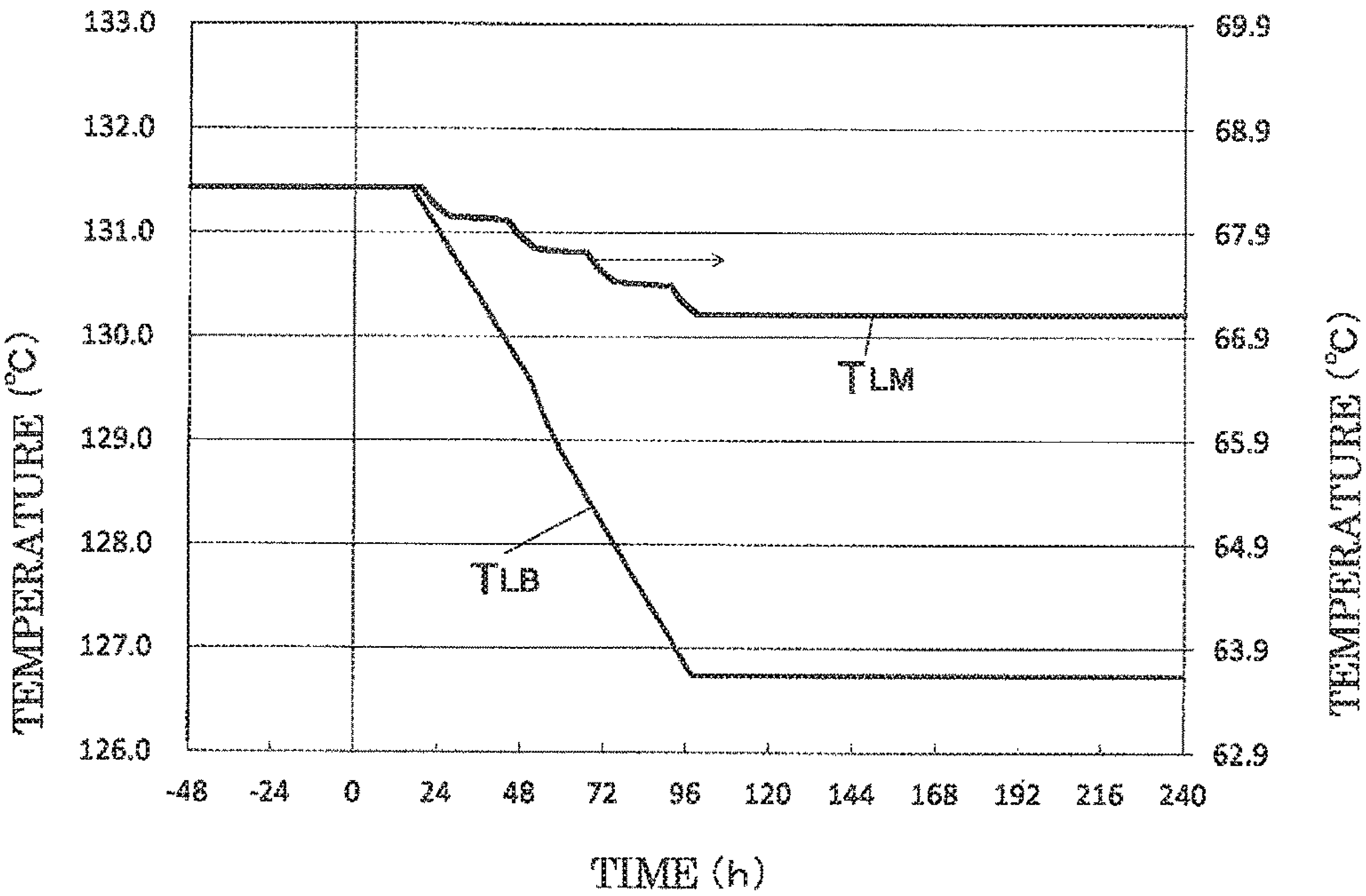
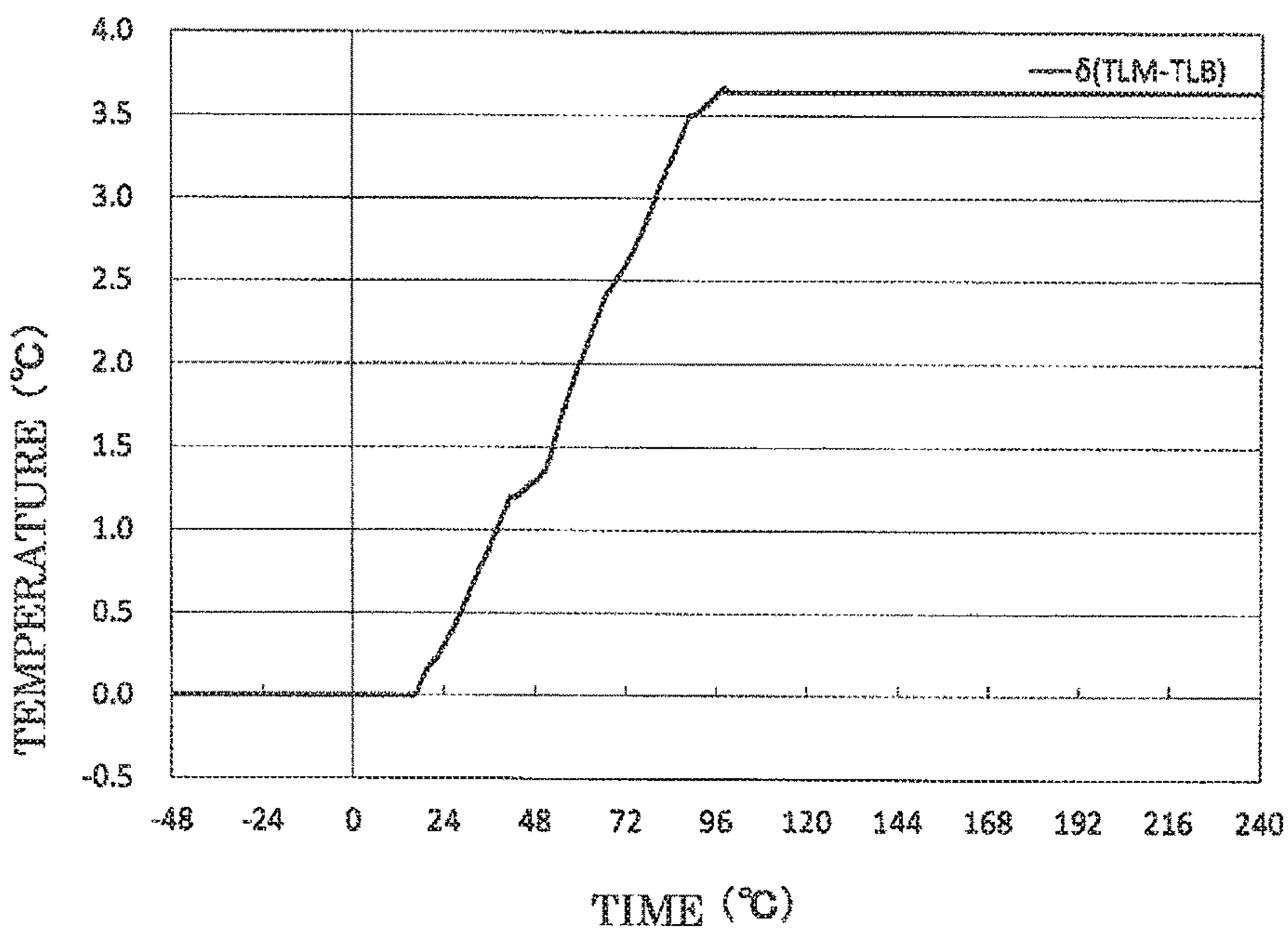

35
34
33
32
31
30
29
28
27
26
25
66.0
65.0
64.0
63.0
62.0
61.0
60.0
59.0
58.0
57.0
56.0
-48
-24
0
24
48
72
96
120
144
168
192
216
240
TEMPERATURE (°C)
TEMPERATURE (°C)
TIME (h)
TTA
TLT

Fig. 23



133.0
132.0
131.0
130.0
129.0
128.0
127.0
126.0
69.9
68.9
67.9
66.9
65.9
64.9
63.9
62.9
TEMPERATURE (°C)
TEMPERATURE (°C)
TLM
TLB
-48 -24 0 24 48 72 96 120 144 168 192 216 240
TIME (h)

Fig. 24



4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
δ(TLM-TLB)
TEMPERATURE (°C)
-48 -24 0 24 48 72 96 120 144 168 192 216 240
TIME (°C)

Fig. 25

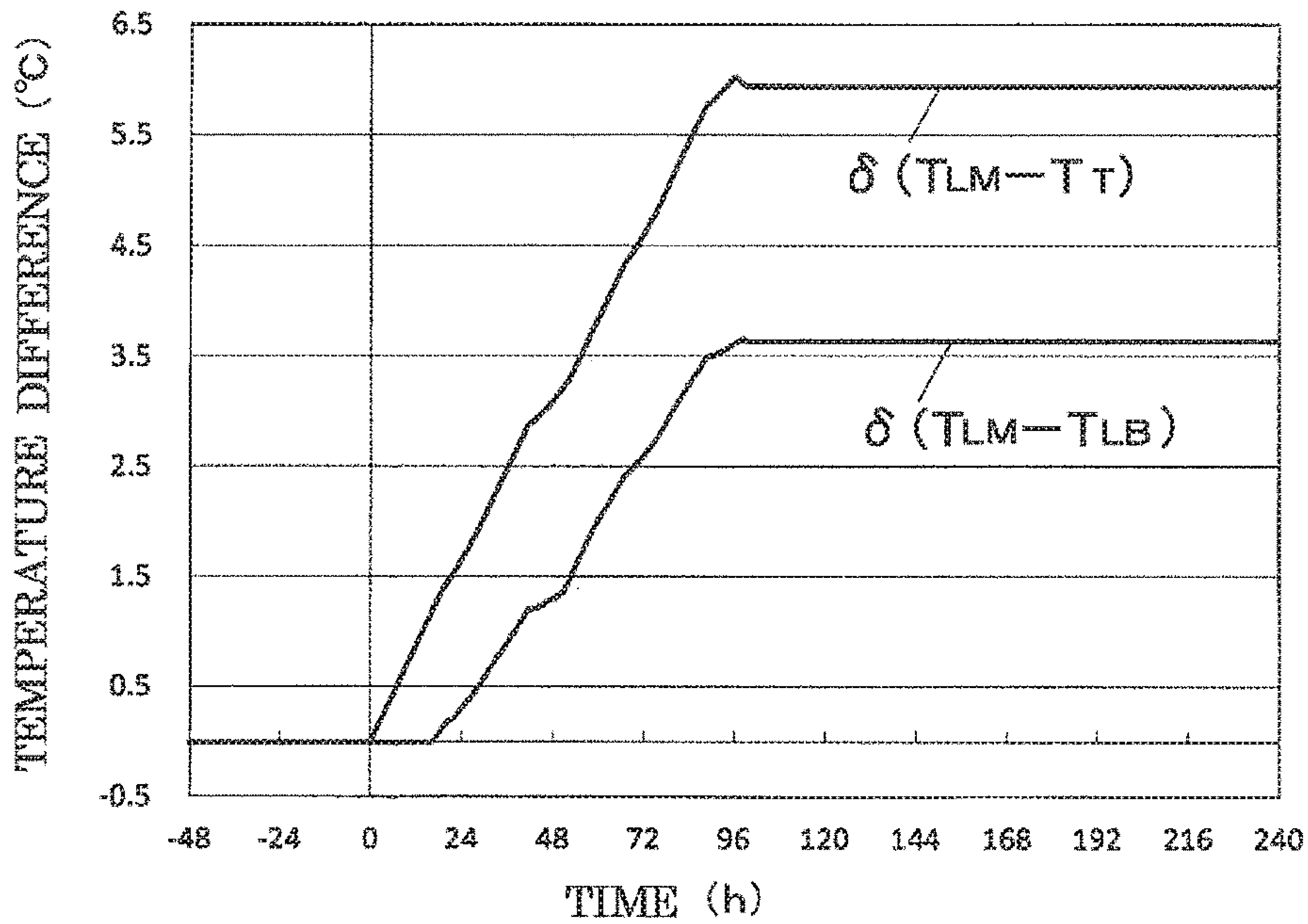

6.5
5.5
4.5
3.5
2.5
1.5
0.5
-0.5
TEMPERATURE DIFFERENCE (°C)
δ (TLM—TT)
δ (TLM—TLB)
-48
-24
0
24
48
72
96
120
144
168
192
216
240
TIME (h)

Fig. 26

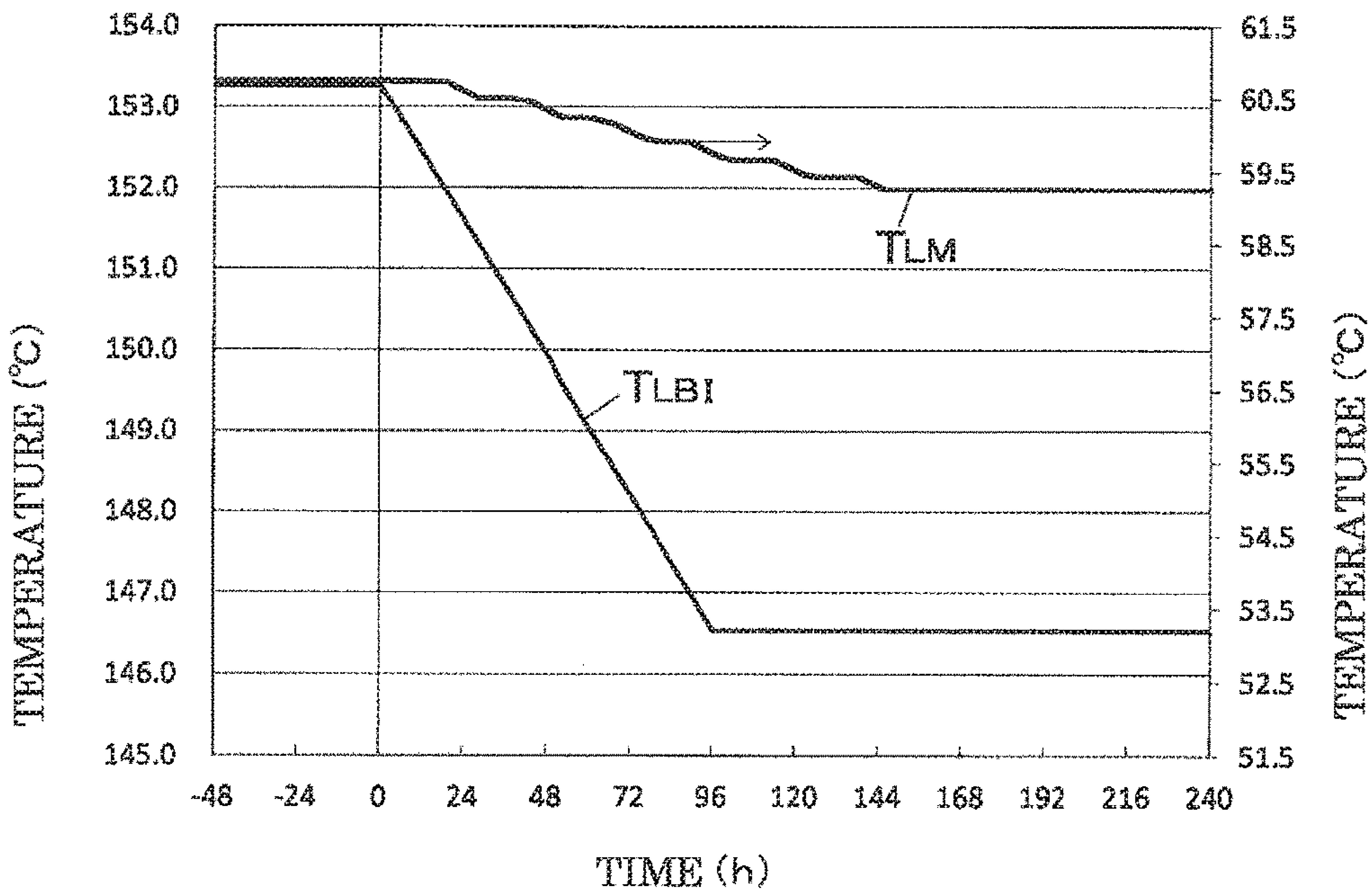

154.0
153.0
152.0
151.0
150.0
149.0
148.0
147.0
146.0
145.0
TEMPERATURE (°C)
61.5
60.5
59.5
58.5
57.5
56.5
55.5
54.5
53.5
52.5
51.5
TEMPERATURE (°C)
TLM
TLBI
-48
-24
0
24
48
72
96
120
144
168
192
216
240
TIME (h)

Fig. 27

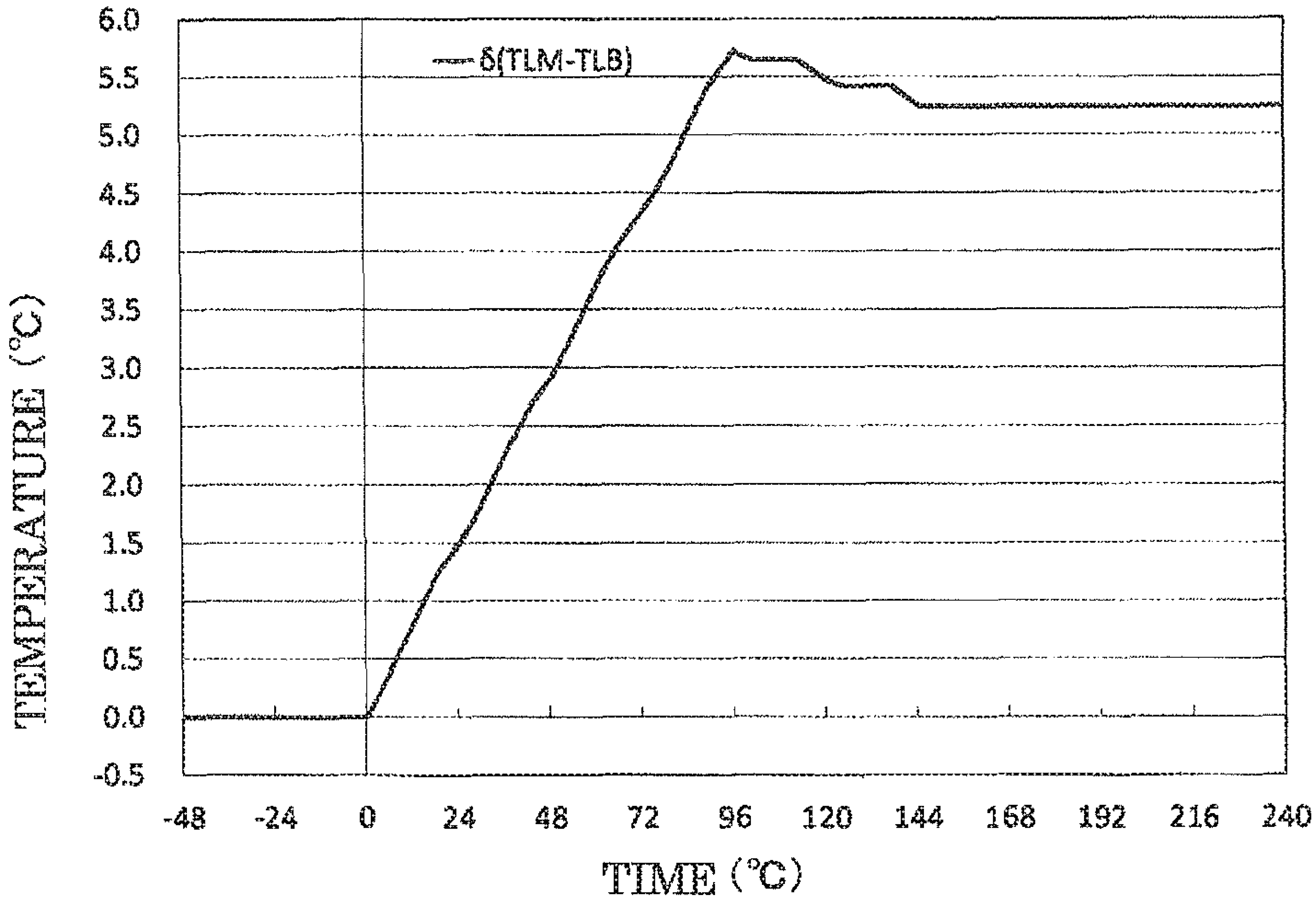

δ(TLM-TLB)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
TEMPERATURE (°C)
-48 -24 0 24 48 72 96 120 144 168 192 216 240
TIME (°C)

Fig. 28

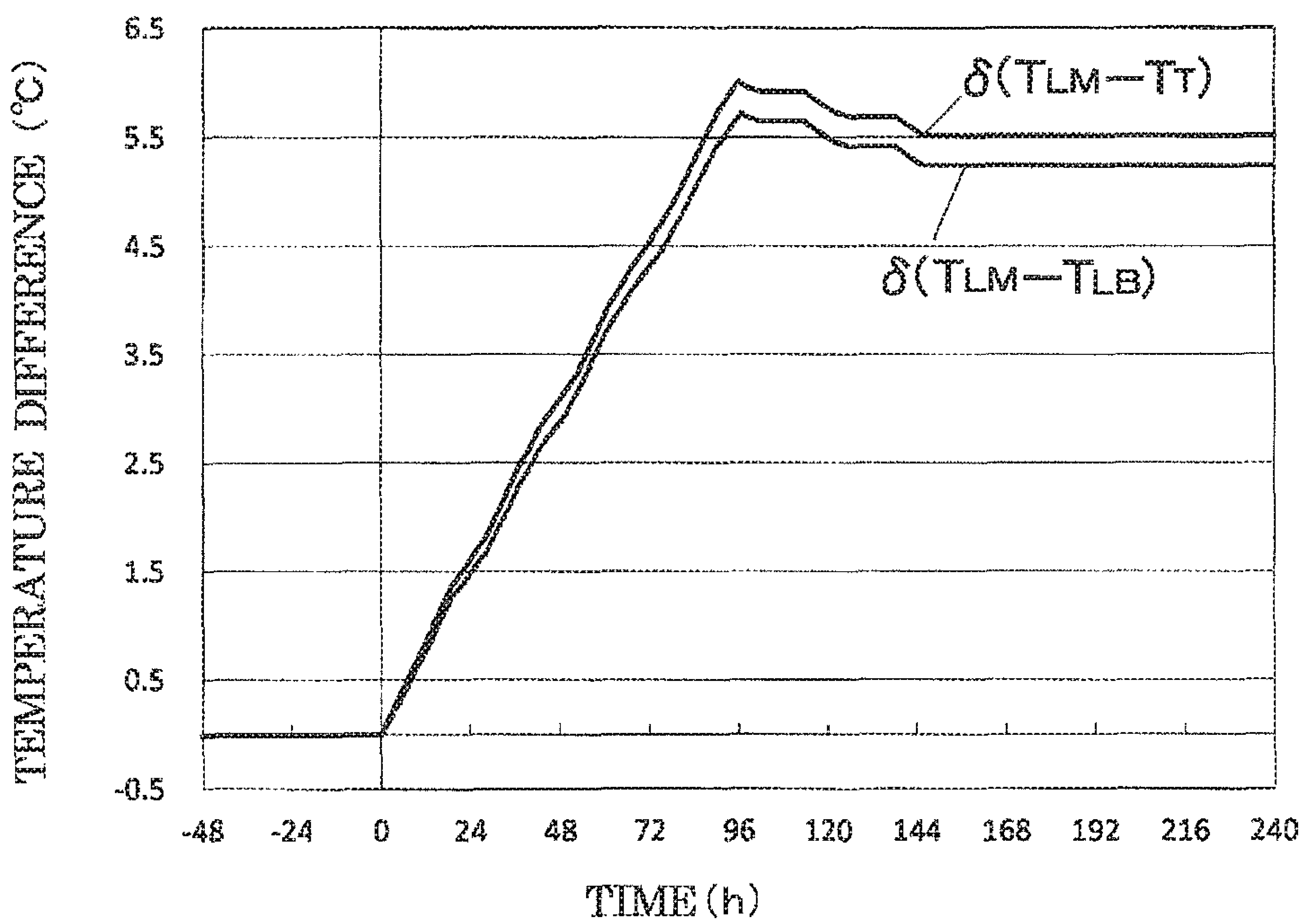
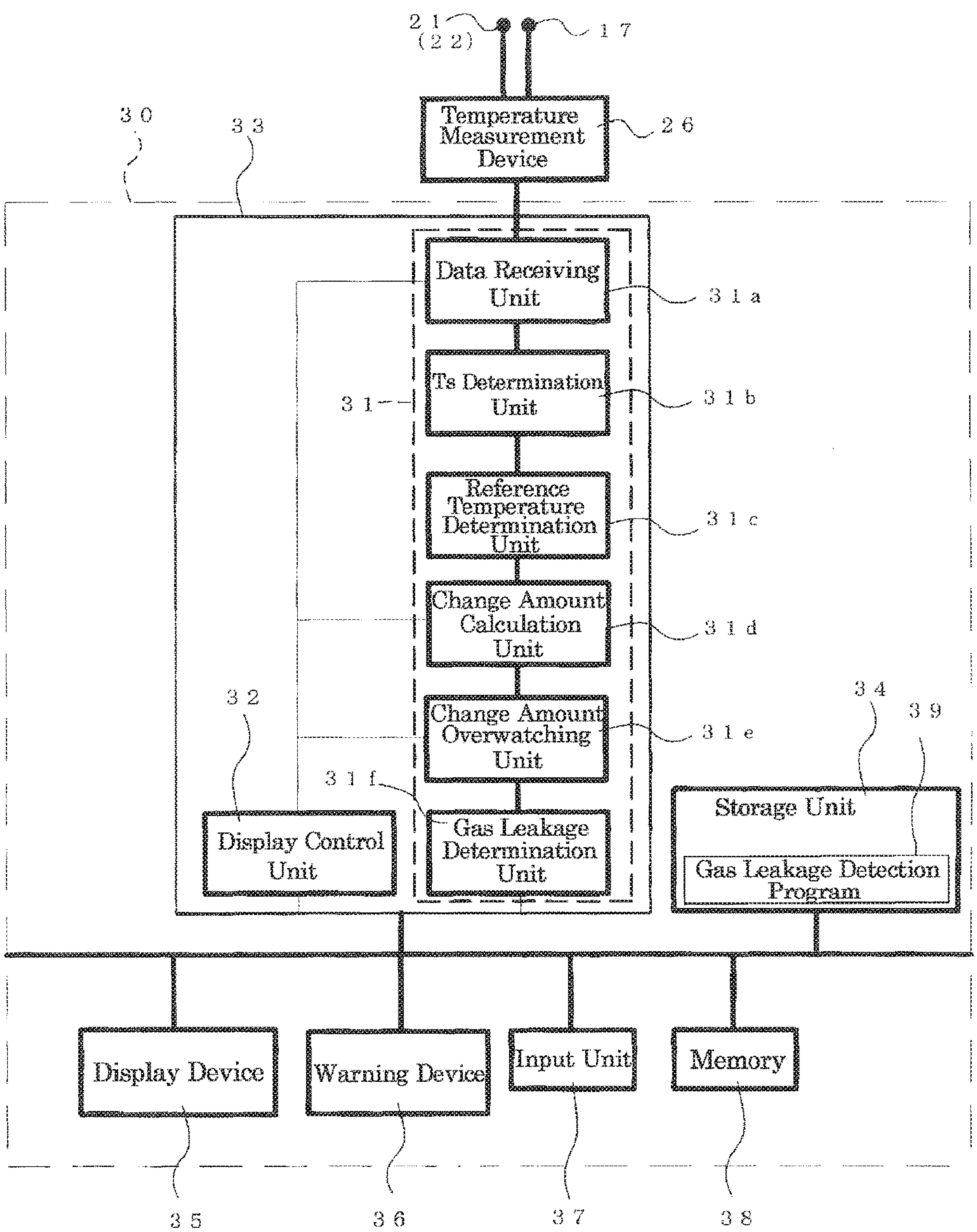
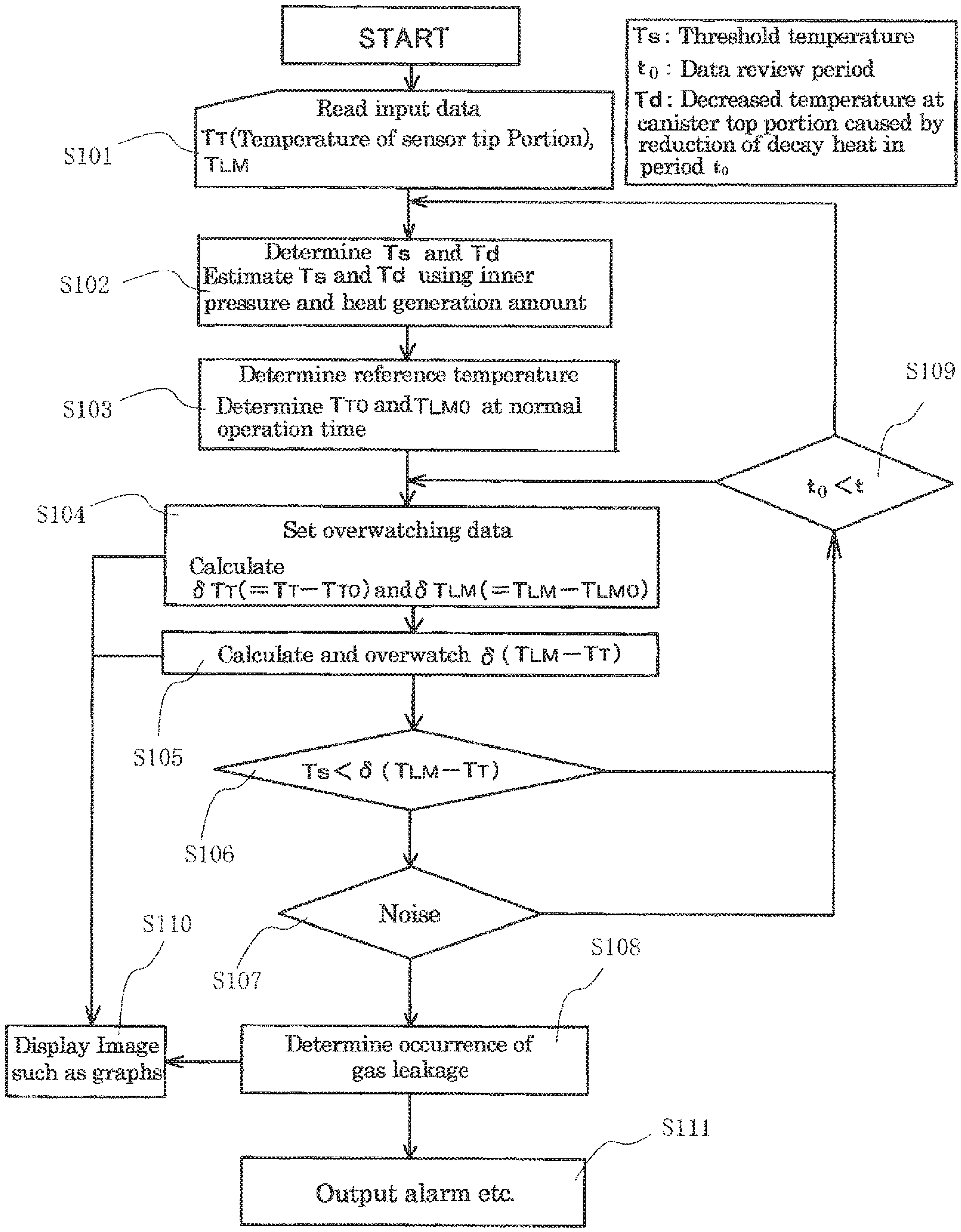

δ(TLM—TT)
δ(TLM—TLB)
6.5
5.5
4.5
3.5
2.5
1.5
0.5
-0.5
TEMPERATURE DIFFERENCE (°C)
-48 -24 0 24 48 72 96 120 144 168 192 216 240
TIME (h)

Fig. 29



21
(22)
17
Temperature Measurement Device
26
30
33
Data Receiving Unit
31a
Ts Determination Unit
31
31b
Reference Temperature Determination Unit
31c
Change Amount Calculation Unit
31d
Change Amount Overwatching Unit
31e
32
31f
Display Control Unit
Gas Leakage Determination Unit
34
39
Storage Unit
Gas Leakage Detection Program
Display Device
Warning Device
Input Unit
Memory
35
36
37
38

Fig. 30



START
Ts: Threshold temperature
t0: Data review period
Td: Decreased temperature at canister top portion caused by reduction of decay heat in period t0
S101
Read input data
TT (Temperature of sensor tip Portion), TLM
S102
Determine Ts and Td
Estimate Ts and Td using inner pressure and heat generation amount
S103
Determine reference temperature
Determine TT0 and TLM0 at normal operation time
S109
t0 < t
S104
Set overwatching data
Calculate
δTT(=TT−TT0) and δTLM(=TLM−TLM0)
Calculate and overwatch δ(TLM−TT)
S105
Ts < δ(TLM−TT)
S106
Noise
S107
S110
S108
Display Image such as graphs
Determine occurrence of gas leakage
S111
Output alarm etc.

Fig. 31

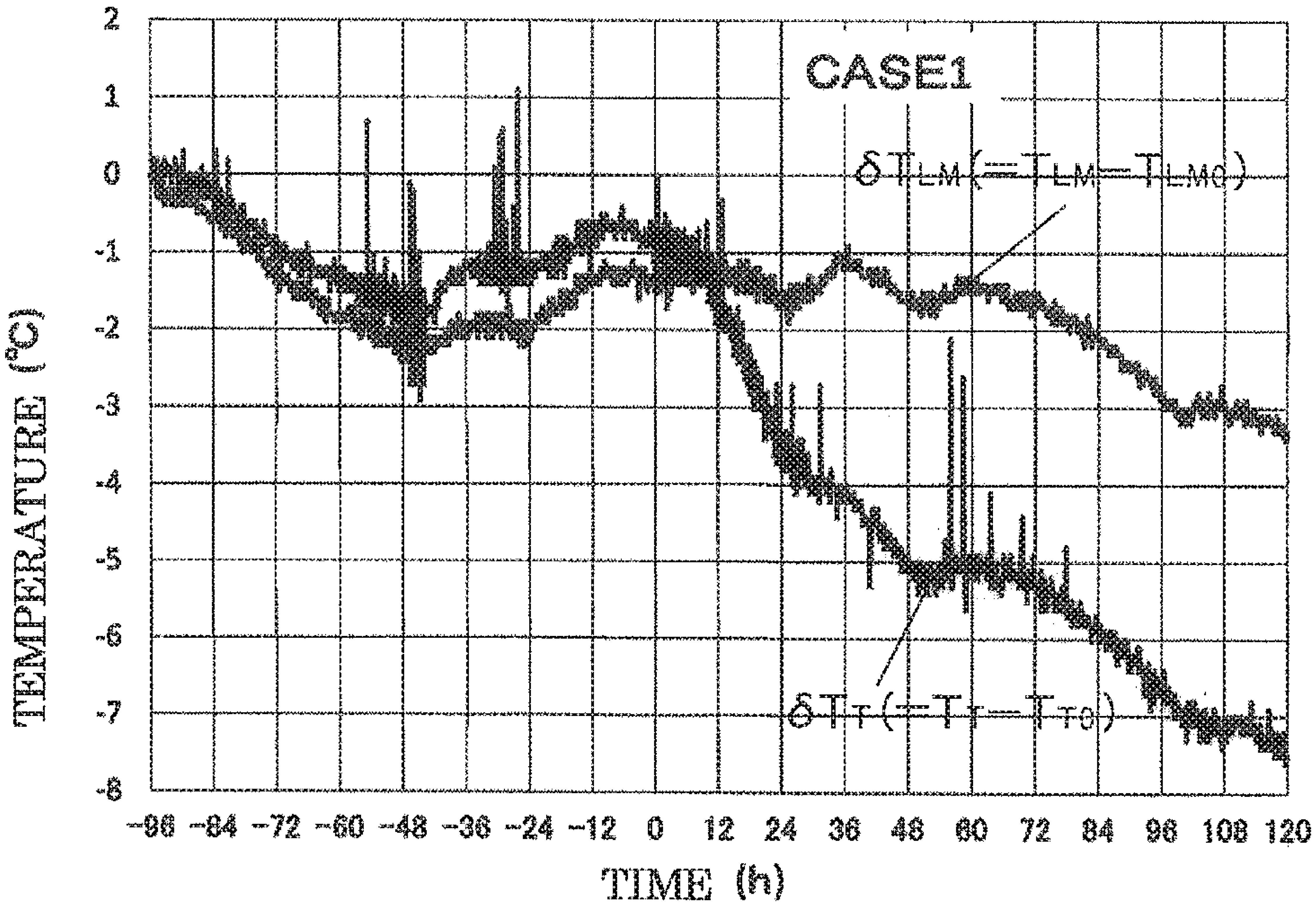

CASE1
δTLM(=TLM−TLM0)
δTT(=TT−TT0)
TEMPERATURE (°C)
TIME (h)
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-96 -84 -72 -60 -48 -36 -24 -12 0 12 24 36 48 60 72 84 96 108 120

Fig. 32

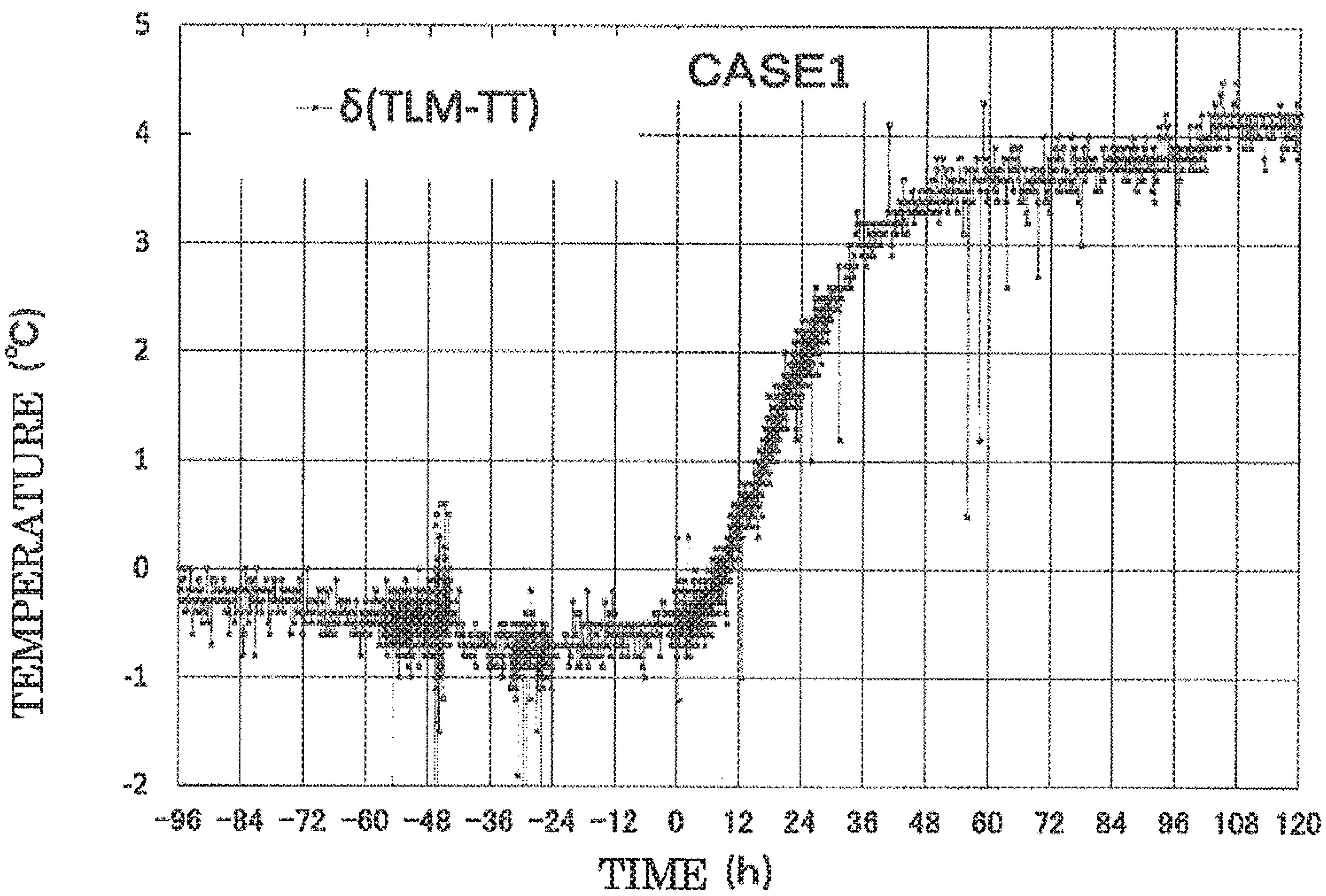

CASE1
δ(TLM-TT)
TEMPERATURE (°C)
TIME (h)
5
4
3
2
1
0
-1
-2
-96 -84 -72 -60 -48 -36 -24 -12 0 12 24 36 48 60 72 84 96 108 120

Fig 33

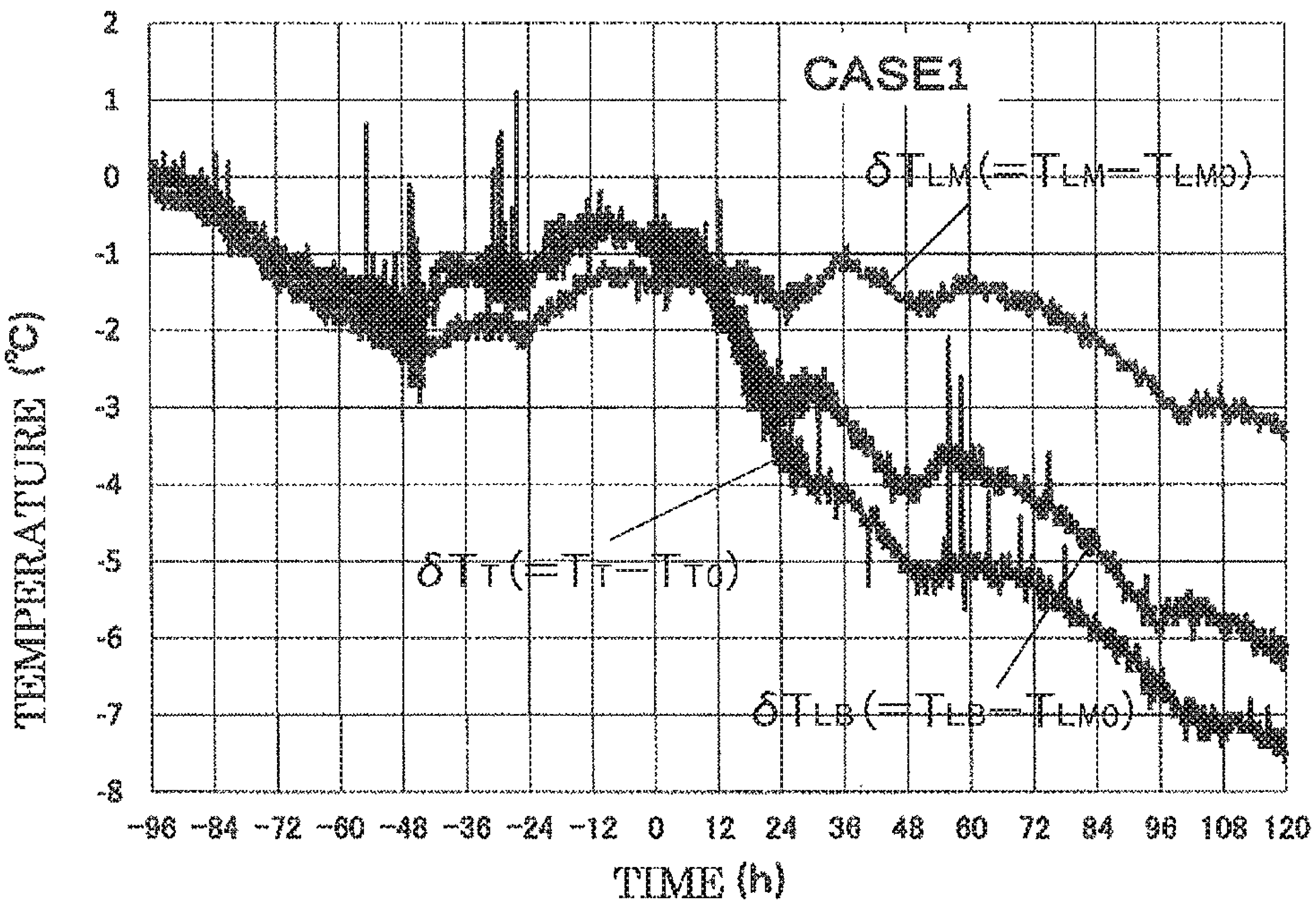

CASE1
δTLM(=TLM−TLM0)
δTT(=TT−TT0)
δTLB(=TLB−TLM0)
TEMPERATURE (°C)
TIME (h)
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
−96 −84 −72 −60 −48 −36 −24 −12 0 12 24 36 48 60 72 84 96 108 120

Fig. 34

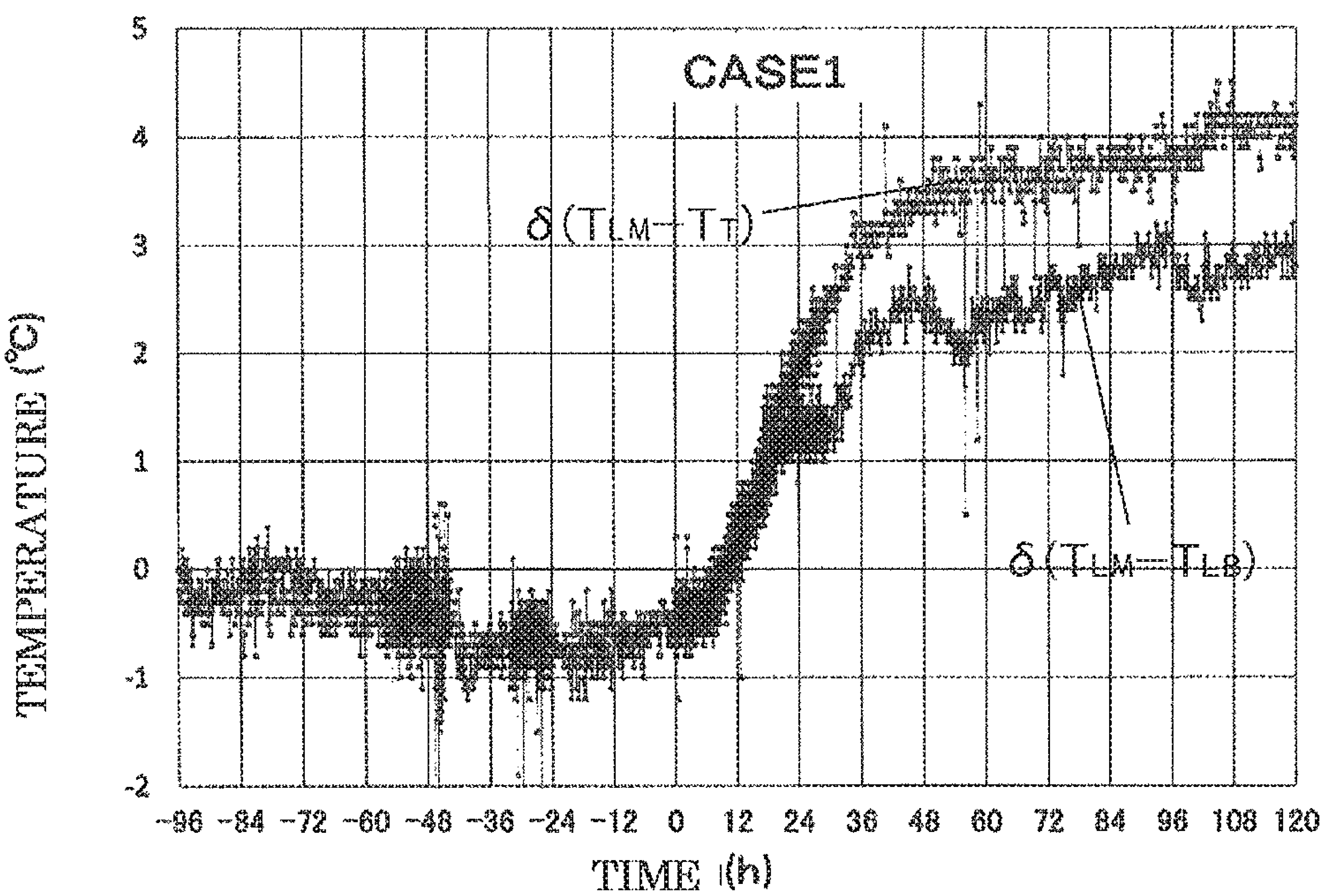
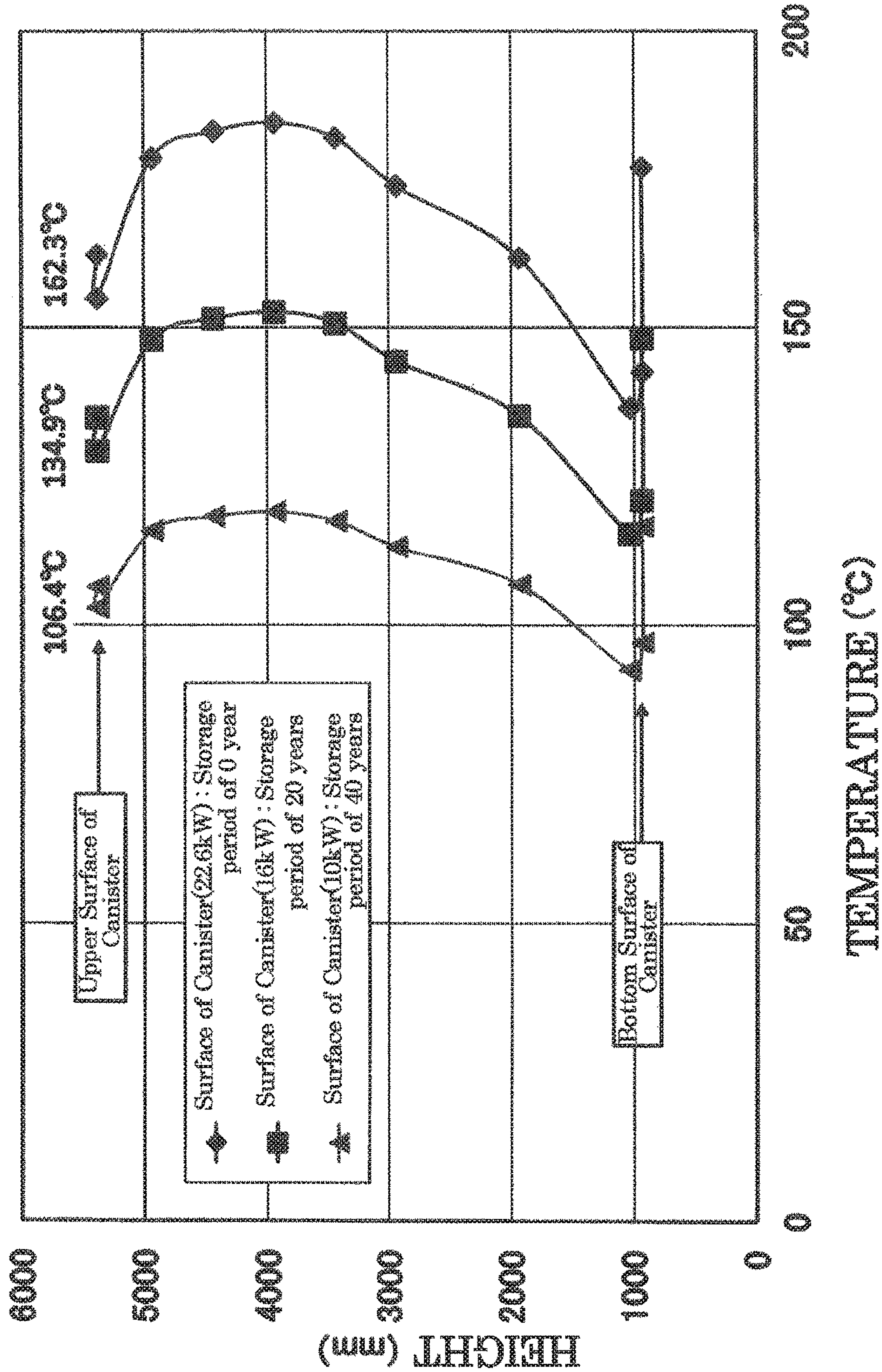

CASE1
δ(TLM−TT)
δ(TLM−TLB)
TEMPERATURE (°C)
TIME (h)
5
4
3
2
1
0
-1
-2
−96 −84 −72 −60 −48 −36 −24 −12 0 12 24 36 48 60 72 84 96 108 120

Fig. 35


HEIGHT (mm)
6000
5000
4000
3000
2000
1000
0
0
50
100
150
200
TEMPERATURE (°C)
162.3°C
134.9°C
106.4°C
Upper Surface of Canister
Bottom Surface of Canister
Surface of Canister(22.6kW) : Storage period of 0 year
Surface of Canister(16kW) : Storage period of 20 years
Surface of Canister(10kW) : Storage period of 40 years

METHOD AND APPARATUS FOR DETECTING GAS LEAKAGE FROM RADIOACTIVE MATERIAL SEALED CONTAINER

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority to Japanese Patent Application No. 2015-182926 filed Sep. 16, 2015, the disclosure of which is hereby incorporated in its entirety by reference.

BACKGROUND

Technical Field

The present invention relates to a method and an apparatus for detecting gas leakage from a radioactive material sealed container. More specifically, the present invention particularly relates to a method and an apparatus for detecting leakage of inactive gas such as helium filled in a metallic canister of a concrete cask.

Related Art

A concrete cask has been a focus of constant attention as a storage means for high radioactive material represented by spent nuclear fuel in a nuclear reactor. The concrete cask is formed of: a cylindrical sealed container made of stainless steel and having a structure that stores spent fuel and seals the same by welding (hereinafter referred to as canister); and a non-sealed concrete-made storage container that has a shielding function and houses the canister (hereinafter referred to as concrete container). The concrete cask is a dry storage facility adapted to remove decay heat of spent fuel contained inside the canister by naturally convecting external air through an air ventilation port provided at upper and lower portions of the concrete container.

The canister has a sealed structure obtained by welding so as not to leak sealed radioactive material to the outside, and also adapted to transfer the decay heat of the spent fuel contained inside the canister via helium to the canister by sealing helium that is inactive gas having thermal conductivity higher than air. Therefore, in the event of helium leakage, there may be a concern that contamination caused by leakage of the radioactive material and insufficient heat removal of the decay heat occur.

In the case of assuming that the concrete cask is installed near coast, cooling air contains salt. Therefore, there may be a concern that a sealing function of the canister is lost by stress corrosion cracking. Additionally, in the case of storing the concrete cask in an inland area also, a deterioration/degradation problem cannot be entirely ignored in consideration of long-term storage, and there may be a concern that helium sealed inside the canister leaks due to a defect, corrosion, and the like at a welding portion of the canister.

A phenomenon of helium leakage is an event to be avoided because radioactive material may be emitted to the environment. Therefore, in the event of such a phenomenon, immediately detecting the event and taking countermeasures are needed. Accordingly, development of a technology to detect helium leakage at an early stage is demanded.

In response to this demand, there is a proposed method of detecting helium leakage, in which a temperature difference between a center temperature at a bottom portion and a center temperature at a top portion in a canister is monitored, and in the case where the temperature difference is increased and a feeding air temperature is decreased, occurrence of gas leakage is determined (JP 2005-265443 A).

However, according to the technology disclosed in JP 2005-265443 A, since it is necessary to measure the temperatures at two points of the top portion and the bottom portion of the canister housed inside the concrete container, construction work for installing thermocouples at the two points of the top portion and the bottom portion of the cask is required. However, depending on a structure of an air inlet port of the concrete cask, the construction work to directly install the thermocouple at the bottom portion of the canister may be difficult.

SUMMARY

The present invention is directed to providing a method and an apparatus for detecting gas leakage from a canister as a radioactive material sealed container, in which presence of leakage of inactive gas can be detected by utilizing only a peripheral temperature of a canister top portion.

A method for detecting gas leakage from a radioactive material sealed container corresponding to a mode to implement the technical idea of the present invention is a method for detecting leakage of inactive gas from a metallic sealed container of the radioactive material sealed container that includes: the metallic sealed container adapted to store and seal spent fuel and the inactive gas; and a non-sealed concrete-made storage container having a shielding function and adapted to store the metallic sealed container. The method includes:

measuring a temperature at a top portion of the metallic sealed container, a temperature at a bottom portion of a lid portion of the concrete-made storage container facing the top portion of the metallic sealed container, or a temperature of a member existing between the bottom portion of the lid portion and the top portion of the metallic sealed container;

also measuring an inner temperature of the lid portion of the concrete-made storage container; and

estimating presence of leakage of the inactive gas by comparing the temperature at the top portion of the metallic sealed container with the inner temperature of the lid portion of the concrete-made storage container or comparing the inner temperature of the lid portion of the concrete-made storage container with the temperature at the bottom portion of the lid portion of the concrete-made storage container or the temperature of the member existing between the bottom portion of the lid portion and the top portion of the metallic sealed container.

An apparatus for detecting gas leakage from a radioactive material sealed container corresponding to a mode to implement the technical idea of the present invention is an apparatus for detecting leakage of inactive gas from a metallic sealed container of the radioactive material sealed container that includes: the metallic sealed container adapted to store and seal spent fuel and the inactive gas; and a non-sealed concrete-made storage container having a shielding function and adapted to store the metallic sealed container. The apparatus includes:

a first temperature sensor adapted to measure a temperature at a top portion of the metallic sealed container, a temperature at a bottom portion of a lid portion of the concrete-made storage container facing the top portion of the metallic sealed container, or a temperature of a member existing between the bottom portion of the lid portion and the top portion of the metallic sealed container;

a second temperature sensor adapted to measure an inner temperature of the lid portion of the concrete-made storage container; and a gas leakage estimation unit adapted to estimate presence of leakage of the inactive gas by comparing a temperature measured by the first temperature sensor with a temperature measured by the second temperature sensor.

According to the above-described method and the apparatus for detecting gas leakage from a radioactive material sealed container, leakage of filled gas such as helium from the metallic sealed container can be determined only from temperature information in the periphery of the top portion of the metallic sealed container. Therefore, temperature sensor installation work is required only at one place on the top portion side of the metallic sealed container, and construction is simpler compared to the case of installing thermocouples at two places of the top portion and the bottom portion of the metallic sealed container. Especially, construction work for installing the thermocouple at the bottom portion of the metallic sealed container is not needed in the concrete-made storage container including a stepwise air inlet port on a side surface in the periphery of the bottom portion. Therefore, it is much more advantageous in viewpoint of construction work.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic diagram illustrating an embodiment of a method and an apparatus for detecting gas leakage from a radioactive material sealed container according to the present invention;

FIG. **2** is an enlarged cross-sectional view illustrating a concrete lid, a canister lid, and temperature sensors;

FIG. **3** is an explanatory diagram illustrating positions of temperature measurement points in an experiment supporting usability of the present invention;

FIG. **4**A is a schematic drawing of a concrete cask used in helium leakage tests made of a steel plate (concrete filled steel) and having an air inlet port on a bottom portion side surface (Case 1);

FIG. **4**B is a schematic drawing of a concrete cask used in helium leakage tests made of a steel plate (concrete filled steel) and having an air inlet port on a bottom portion side surface using a lid having outlet ducts with low flow resistance (Case 2);

FIG. **4**C is a schematic drawing of a concrete cask used in helium leakage tests made of reinforced concrete and having an air inlet port at a bottom portion (Case 3);

FIG. **5** is a graph illustrating change of a canister top portion center temperature T_T and change of a canister bottom portion center temperature T_B relative to inner pressure of a canister before and after helium leakage in Case 1;

FIG. **6** is a graph illustrating a relation of the canister top portion center temperature T_T and the canister bottom portion center temperature T_B with a feeding air temperature T_{IN} before and after helium leakage in Case 1;

FIG. **7** is a graph illustrating change of a canister top portion center temperature T_T and change of a canister bottom portion center temperature T_B relative to inner pressure of a canister before and after helium leakage in Case 2;

FIG. **8** is a graph illustrating a relation of the canister top portion center temperature T_T and the canister bottom portion center temperature T_B with an feeding air temperature T_{IN} before and after helium leakage in Case 2;

FIG. **9** is a graph illustrating change of a canister top portion center temperature T_T and change of a canister bottom portion center temperature T_B relative to inner pressure of a canister before and after helium leakage in Case 3;

FIG. **10** is a graph illustrating a relation of the canister top portion center temperature T_T and the canister bottom portion center temperature T_B with an feeding air temperature T_{IN} before and after helium leakage in Case 3;

FIG. **11** is a graph illustrating change of the canister top portion center temperature T_T relative to the inner pressure of the canister before and after helium leakage in Case 1;

FIG. **12** is a graph illustrating a relation between the canister top portion center temperature T_T and an air temperature T_{LA} between a concrete lid bottom portion and the canister top portion before and after helium leakage in Case 1;

FIG. **13** is a graph illustrating a relation between the canister top portion center temperature T_T and a concrete lid bottom portion temperature T_{LB} relative to the inner pressure of the canister before and after helium leakage in Case 1;

FIG. **14** is a graph illustrating a relation between the canister top portion center temperature T_T and a concrete lid inner temperature T_{LM} before and after helium leakage in Case 1;

FIG. **15** is a graph illustrating a relation between the canister top portion center temperature T_T and a concrete lid upper portion temperature T_{LT} before and after helium leakage in Case 1;

FIG. **16** is a graph illustrating a relation between the canister top portion center temperature T_T and the feeding air temperature T_{IN} before and after helium leakage in Case 1;

FIG. **17** is a graph illustrating a relation between the concrete lid bottom portion temperature T_{LB} and the lid inner temperature T_{LM} before and after helium leakage in Case 1;

FIG. **18** is a graph illustrating a relation between the lid bottom portion temperature T_{LB} and the lid inner temperature T_{LM} before and after helium leakage in Case 3;

FIG. **19** is a graph illustrating a relation between daily fluctuation of the concrete lid upper portion air temperature T_{TA} and change of the canister top portion center temperature T_T before and after helium leakage in Case 1;

FIG. **20** is a graph illustrating time variation of temperatures at six measurement points illustrated in FIG. **3** before and after helium leakage in Case 1;

FIG. **21** is a graph illustrating temperature distribution from a point of measuring the concrete lid upper portion air temperature T_{TA} to a point of measuring the canister top portion temperature T_T in Case 1;

FIG. **22** is a graph illustrating a relation between the concrete lid upper portion temperature T_{LT} and the concrete lid upper portion air temperature T_{TA} before and after helium leakage in Case 1;

FIG. **23** is a graph illustrating a relation between the lid bottom portion temperature T_{LB} and the lid inner temperature T_{LM} before and after helium leakage in Case 1;

FIG. **24** is a graph illustrating a relation between a fluctuation difference $\delta(T_{LM}-T_{LB})$ between the lid bottom portion temperature T_{LB} and the lid inner temperature T_{LM} before and after helium leakage in Case 1;

FIG. **25** is a graph illustrating fluctuation differences $\delta(T_{LM}-T_T)$ and $\delta(T_{LM}-T_{LB})$ between the lid bottom portion temperature T_{LB}, the canister top portion center temperature T_T, and the lid inner temperature T_{LM} before and after helium leakage in Case 1;

FIG. **26** is a graph illustrating a relation between the lid bottom portion temperature T_{LB} and the lid inner temperature T_{LM} before and after helium leakage when temperature sensors of Case 1 are arranged in a state as illustrated in FIG. **2**;

FIG. **27** is a graph illustrating a fluctuation difference $\delta(T_{LM}-T_{LB})$ between the lid bottom portion temperature T_{LB} and the lid inner temperature T_{LM} before and after helium leakage when temperature sensors of Case 1 are arranged in a state as illustrated in FIG. **2**;

FIG. **28** is a graph illustrating fluctuation differences $\delta(T_{LM}-T_T)$ and $\delta(T_{LM}-T_{LB})$ between the lid bottom portion temperature T_{LB}, canister top portion center temperature T_T, and lid inner temperature T_{LM} before and after helium leakage when temperature sensors of Case 1 are arranged in a state as illustrated in FIG. **2**;

FIG. **29** is a functional block diagram illustrating an embodiment of the apparatus for detecting gas leakage from a radioactive material sealed container according to the present invention;

FIG. **30** is a flowchart illustrating an embodiment of an apparatus and a method for detecting gas leakage from a radioactive material sealed container according to the present invention;

FIG. **31** is a graph illustrating an exemplary relation of time variations of differences of the canister top portion center temperature T_T and the lid inner temperature T_{LM} from reference temperatures before and after helium leakage in Case 1;

FIG. **32** is a graph illustrating an exemplary time variation of the difference $\delta(T_{LM}-T_{LB})$ from a reference temperature of the temperature difference $(T_{LM}-T_{LB})$ between the lid bottom portion temperature T_{LB} and the lid inner temperature T_{LM} before and after helium leakage in Case 1;

FIG. **33** is a graph illustrating an exemplary relation of time variations of differences of the lid inner temperature T_{LM}, the lid bottom portion temperature T_{LB}, and the canister top portion center temperature T_T from reference temperatures before and after helium leakage in an embodiment in which a temperature of a temperature sensor set closest to the canister top portion is substituted as the canister top portion center temperature T_T and a temperature of a metal plate on a bottom surface of the concrete lid is indicated as the lid bottom portion temperature T_{LB} in Case 1;

FIG. **34** is a graph illustrating an exemplary time variation of differences from reference temperatures of the temperature difference $(T_{LM}-T_{LB})$ between the lid inner temperature T_{LM} and the lid bottom portion temperature T_{LB}, and the temperature difference $(T_{LM}-T_T)$ between the lid inner temperature T_{LM} and the canister top portion center temperature T_T before and after helium leakage in the embodiment in which the temperature of the temperature sensor set closest to the canister top portion is substituted as the canister top portion center temperature T_T and the temperature of the metal plate on the bottom surface of the concrete lid is indicated as the lid bottom portion temperature T_{LB} in Case 1; and

FIG. **35** is a graph illustrating an exemplary secular change of temperature distribution in a vertical direction of the canister in Case 1.

DETAILED DESCRIPTION

In the following, an embodiment as an exemplary aspect to implement a technical idea of the present invention will be described in detail using the drawings. In the present embodiment, exemplified is a case where an apparatus for detecting gas leakage is applied to a radioactive material sealed container illustrated in FIG. **1**. However, a structure, a shape, quality of material, and the like of the radioactive material sealed container in which the present invention is applied are not limited to the example illustrated in FIG. **1**.

The radioactive material sealed container of the present embodiment is a concrete-made dry cask or simply called a concrete cask, and formed of: a metallic sealed container having a structure adapted to store and seal spent fuel by welding (hereinafter referred to as a canister **1**); and a non-sealed concrete-made storage container having a shielding function and adapted to house the canister **1** (hereinafter referred to as a concrete container **2**). The radioactive material sealed container of the present embodiment has a structure in which decay heat of the spent fuel contained inside the canister **1** is removed by naturally convecting external air **5** via an air inlet port **7** and an outlet port **8** which are air ventilation ports provided at upper and lower portions of the concrete container **2**.

The canister **1** is supported by a supporting leg **6**, and forms a flow passage **9** in a space with the concrete container **2** around the canister.

Meanwhile, a bar-shaped thermometer **4** is embedded in a lid portion of the concrete container **2** (hereinafter simply referred to as a concrete lid **3**).

The concrete lid **3** is basically formed of concrete as a main constituent material in order to shield neutrons in the same manner as the concrete container **2**.

For example, as illustrated in FIG. **2**, the concrete lid **3** has a shielding structure formed by sequentially stacking, from the top, a metal plate **10** to be an outer shell, a concrete material **11**, a metal plate **12** to be a partition, a heat insulator **13**, and a metal plate **14** to be an outer shell on a bottom side. A bottom portion of the concrete lid **3** represents the metal plate **14** in the case of the present embodiment. In the following, the bottom portion of the concrete lid **3** is described as the bottom portion **14** of the concrete lid **3**.

The canister **1** is generally made of metal such as stainless steel and formed as a cylindrical sealed container by welding. The canister **1** generally has a double lid and is sealed by welding after the container containing a radioactive material and a space between an inner lid and an outer lid are filled with inactive gas, but may also have a single lid depending on circumstances. Therefore, in the present embodiment, a top portion of the canister **1** (hereinafter referred to as a canister top portion $\mathbf{1}_T$) means a lid portion of the canister **1** facing the concrete lid **3**.

As the gas sealed inside the canister **1**, for example, helium (He) is preferable. Helium is the inactive gas having thermal conductivity higher than air. The present invention can be implemented under negative pressure, but heat of the radioactive material is transmitted to the canister **1** and heat removal performance may be improved by making helium to positive pressure. Furthermore, helium may also be kept at high pressure in order to improve heat removal performance, and for example, in a case implemented in United States, helium is kept at about 8 atmospheric pressure.

Note that filled gas is not necessarily limited to helium, and other inactive gases having the thermal conductivity higher than air may also be used as well. In this case, the adopted inactive gas is to be a detecting target.

Meanwhile, the structure of the concrete cask may be a concrete cask made of a steel plate (CFS: concrete filled steel) illustrated in FIG. **4**A, a concrete cask made of CFS using a lid having outlet ducts with low flow resistance illustrated in FIG. **4**B, or a concrete cask made of reinforced concrete (RC) illustrated in FIG. **4**C.

Furthermore, a form of an air inlet port may be a stepwise shape as illustrated in FIGS. **4**A and **4**B or a cross groove shape as illustrated in FIG. **4**C. The air inlet port having the cross groove shape is formed of: a cross-shaped groove that passes a center of a bottom portion of the concrete container **2**; and a vertical hole penetrating the inside of the container at an intersecting portion with the groove.

Additionally, as for cooling fluids to be introduced into the concrete container **2**, the external air is directly made to flow inside in the present embodiment, but depending on circumstances, air that has been adjusted to have a predetermined temperature range and humidity or a cooling gas other than air may also be fed inside.

The apparatus for detecting gas leakage according to the present embodiment applied to the above-described concrete cask includes: a first temperature sensor **21** adapted to measure a canister top portion temperature T_T that is a surface temperature of the canister top portion $\mathbf{1}_T$, a temperature T_{LB} of the bottom portion **14** of the concrete lid **3** facing the canister top portion $\mathbf{1}_T$, or a temperature T_{LBI} of a member existing between the bottom portion **14** of the concrete lid **3** and the canister top portion $\mathbf{1}_T$; a second temperature sensor **17** adapted to measure a lid inner temperature T_{LM} of the concrete lid **3** facing the canister top portion $\mathbf{1}_T$; and, a gas leakage estimation unit **31** adapted to estimate presence of inactive gas leakage by comparing a measured temperature of the first temperature sensor **21** with a measured temperature of the second temperature sensor **17**. In other words, when significant fluctuation between the measured temperatures of the first temperature sensor **21** and the second temperature sensor **17** are recognized, it is estimated that inactive gas leakage has occurred.

Here, at the time of monitoring leakage determination data, a difference between two temperatures is preferably used in viewpoint of easy evaluation. For example, it may be considered to calculate, as a change amount, a difference between each of average temperatures of the two temperatures during a period deemed as proper operation time without occurrence of helium leakage or each of the two temperatures at a specific time point deemed as the proper operation time (referred to as reference temperature) and each of the two temperatures at the time of measurement, and then further obtain and monitor a difference between these change amounts. In this case, when the difference between the temperature change amounts tends to increase, it can be determined that leakage is occurring.

Furthermore, in the case of directly comparing actual measurement temperatures of the two temperatures T_T and T_{LM} or actual measurement temperatures of the temperatures T_{LB} and T_{LM}, when the temperature difference between both temperatures tends to be reduced, it can be determined that leakage is occurring. Furthermore, in the case of displaying two actual measurement temperatures to be compared also, the two actual measurement temperatures are multiply displayed, making the respective comparing average values of the two actual measurement temperatures the same. Consequently, when a deviation state in a graph illustrating changes of temperatures of both temperatures tends to be enlarged, it can be determined that leakage is occurring.

Preferably, the first temperature sensor **21** directly measures the canister top portion temperature T_T in terms of improving inactive gas leakage detection sensitivity. However, in the case of making a temperature sensor such as a thermocouple contact the canister top portion $\mathbf{1}_T$ directly, there may be problems such as galvanic corrosion caused by the canister **1** contacting a different kind of metal, and damage/degradation of the temperature sensor by radioactive rays.

On the other hand, in a method of measuring the temperature at the canister top portion $\mathbf{1}_T$ with a radiation thermometer from above a penetration hole opened at the concrete lid **3**, there may be a problem such as damage of the shielding function because it is necessary to enlarge a diameter of the penetration hole in order to enable adjustment of a focal point of the radiation thermometer. Therefore, this method is not realistic.

To solve the above-described problem, the inventor has found that temperature information having high correlation with the canister top portion temperature T_T and excellently reflected with change of the canister top portion temperature T_T can be obtained by measuring a temperature of a member that receives influence of the canister top portion temperature T_T by using a contact type thermometer such as a thermocouple or a thermistor, without causing corrosion of the canister **1** and damage/degradation of the temperature sensor **21**. Furthermore, the inventor made it clear, from experiments/analysis, that the temperature information not only having high correlation with the canister top portion temperature T_T but also having temperature value close thereto can be obtained by measuring, with the contact type thermometer such as the thermocouple or the thermistor, a temperature of a member such as the metal plate **20** made to project close to the canister top portion $\mathbf{1}_T$ from the metal plate **14** corresponding to the bottom portion of the concrete lid **3** as illustrated in FIG. **2**.

Here, it is not important to grasp an exact temperature in measuring the canister top portion temperature T_T, and it is important to grasp movement of temperature change. Considering this, the inventor has found substituting, for the canister top portion temperature T_T, the temperature of the metal plate **20** located at a tip of the bar-shaped thermometer **4** installed at a position closest to the surface of the canister top portion $\mathbf{1}_T$.

Therefore, in the present embodiment, as the temperature of the member that receives influence of the canister top portion temperature T_T, the temperature T_{LB} at the bottom portion **14** of the concrete lid **3** facing the canister top portion $\mathbf{1}_T$ or the temperature T_{LBI} of the member existing between the bottom portion **14** of the concrete lid **3** and the canister top portion $\mathbf{1}_T$ is measured.

The member that receives influence of the canister top portion temperature T_T is a member heated by radiation from the canister top portion $\mathbf{1}_T$. As the member that receives influence of the surface temperature T_T of the canister top portion $\mathbf{1}_T$, more specifically, the metal plate corresponding to the bottom portion **14** of the concrete lid **3** and a metal component projecting to the canister top portion $\mathbf{1}_T$ side more than the bottom portion **14** may be exemplified.

In the present embodiment, the metal plate **20** located at the tip of the bar-shaped thermometer **4** projecting toward the canister top portion $\mathbf{1}_T$ from the bottom portion **14** of the concrete lid **3** is adopted as the member that receives influence of the canister top portion temperature T_T.

In the description of the present invention, a temperature of the member that receives influence of the canister top portion temperature T_T including the bottom portion **14** of the concrete lid **3** is described as a lid bottom portion temperature T_{LB} for convenience of the description. More specifically, the temperature T_{LB} at the bottom portion **14** of the concrete lid **3** and the temperature T_{LBI} of the member existing between the bottom portion **14** of the concrete lid **3** and the canister top portion $\mathbf{1}_T$ are described as the lid bottom portion temperature T_{LB}.

The second temperature sensor **17** measures a temperature at a portion that hardly receives influence of the canister top portion temperature T_T inside the concrete lid **3**. In the description of the present invention, the temperature at a portion that hardly receives influence of the canister top portion temperature T_T inside the concrete lid **3** is described as a lid inner temperature T_{LM}.

In the present embodiment, the lid inner temperature T_{LM} corresponds to a temperature at the concrete **11** of the concrete lid **3**.

In the present embodiment, the bar-shaped thermometer **4** including the first temperature sensor **21** and the second temperature sensor **17** is used. Furthermore, the bar-shaped thermometer **4** is inserted into the relatively small penetration hole **25** opened at the concrete lid **3**, thereby providing the first temperature sensor **21** at the bottom portion of the concrete lid **3** and also providing the second temperature sensor **17** inside the concrete lid **3**.

The first temperature sensor **21** and the second temperature sensor **17** are installed on a vertical line passing a center in a diameter direction of the canister top portion $\mathbf{1}_T$ and the concrete lid **3**, namely, on a center axis. Temperature change at the canister top portion $\mathbf{1}_T$ in the event of helium leakage is largest at the center position of the canister top portion $\mathbf{1}_T$. Therefore, by monitoring the temperature at the center position of the canister top portion $\mathbf{1}_T$, detection sensitivity can be improved, and furthermore, it is expected that highly reliable gas leakage detection can be performed.

However, accurately arranging the respective temperature sensors **17**, **21** on the center axis is not an indispensable condition, and the temperature sensors may also be arranged at a position distant from the center, such as a position close to an edge of the canister top portion $\mathbf{1}_T$ or the concrete lid **3**. Furthermore, the respective temperature sensors **17**, **21** may also be arranged on a different vertical axis line.

The first temperature sensor **21** provided at the tip of the bar-shaped thermometer **4** measures the temperature at the metal plate **20** as the member that receives influence of the surface temperature of the canister top portion $\mathbf{1}_T$.

In the case of the present embodiment, the first temperature sensor **21** is provided on a front surface, i.e. an undersurface, of the metal plate **20** facing the canister top portion $\mathbf{1}_T$ and measures the lid bottom portion temperature T_{LB}.

However, depending on circumstances, the first temperature sensor **22** may be arranged on a back surface, i.e. an upper surface, of the metal plate **20** facing the heat insulator **19** as indicated by a virtual line in FIG. **2**, and may also measure a back surface temperature T_{LBI} of the metal plate **20**. In this case, the first temperature sensor **22** is prevented from being damaged by radioactive rays because the metal plate **20** functions as a metallic protection cover and shields the radioactive rays such as γ-rays. Furthermore, the back surface temperature T_{LBI} of the metal plate **20** is little different from the front surface temperature T_{LB} of the metal plate **20**, and may also be used as a substitute of the top portion temperature T_T of the metallic sealed container.

As the respective temperature sensors **17**, **21** or **22**, for example, preferably the thermometer such as a thermocouple or a thermistor is used. In this case, in addition to a merit that the structure is simple and inexpensive, long-term stable operation can be expected because of the simple structure. These two temperature sensors **17**, **21** or **22** are electrically connected to a temperature measurement device **26**, and temperature measurement is performed by utilizing thermoelectromotive force provided by a Seebeck effect.

The bar-shaped thermometer **4** is formed by sequentially stacking, from the top, a metal plate **15** to be a lid, a concrete **16**, a metal plate **18**, the heat insulator **19**, and the metal plate **20** to be the bottom as illustrated in FIG. **2**, and formed to have a shielding structure in the same manner as the concrete lid **3** by a peripheral surface of the bar-shaped thermometer being coated with a metallic protection cylinder **24** and covered with a lid using the metal plate **15**.

Furthermore, the bar-shaped thermometer **4** includes the thermocouple **17** as the second temperature sensor **17** inside the concrete **16** and also includes the thermocouple **21** as the first temperature sensor **21** on the front surface of the metal plate **20**. Therefore, the first temperature sensor **21** and the second temperature sensor **17** are arranged at desired positions of the concrete lid **3** just by closing the penetration hole **25** of the concrete lid **3** by inserting the bar-shaped thermometer **4** into the penetration hole **25**, and furthermore, the shielding function of the concrete lid **3** can be maintained and a stagnation space under the concrete lid **3** is secured, and detection sensitivity can be more improved.

Moreover, since a space between the canister **1** and lid **3** of the concrete container **2** is narrow and forms the stagnation space to provide a heat insulation effect, the top portion temperature T_T of the canister **1** hardly receives influence of the feeding air temperature T_{IN}, and also hardly receives influence of daily fluctuation of the feeding air temperature T_{IN}. Therefore, since leakage of the filled gas from the canister **1**, such as helium, can be determined only from the temperature information in the periphery of the top portion of the canister **1**, complicated determination considering daily fluctuation of an external air temperature is not needed, and reliability of detection is improved.

Meanwhile, the concrete **16** of the bar-shaped thermometer **4** has a thickness same as the concrete **11** of the concrete lid **3**. Furthermore, in the case of the present embodiment, the thickness of the heat insulator **19** of the bar-shaped thermometer **4** is made equal to or more than that of the heat insulator **13** of the concrete lid **3**. Consequently, the metal plate **20** and the first temperature sensor **21** provided at the tip of the bar-shaped thermometer **4** can be arranged closer to the canister top portion $\mathbf{1}_T$ than the concrete lid bottom portion **14**. Additionally, the metallic protection cylinder **24** is preferably formed of material having high heat conductivity.

The bar-shaped thermometer **4** is inserted into the penetration hole **25** of the concrete lid **3** and then fixed by fastening the concrete lid **3** and the metal plate **15** of the bar-shaped thermometer **4** with a bolt **23**. Therefore, only by simple construction work such as providing the penetration hole on the lid portion of the concrete-made storage container, inserting the bar-shaped thermometer into the penetration hole, and then fix the same with the bolt, the second temperature sensor is arranged inside the lid portion of the concrete-made storage container and also the first temperature sensor can be arranged in a range from the bottom portion of the lid portion of the concrete-made storage container to the top portion of the metallic sealed container. Moreover, since the bar-shaped thermometer **4** can be detached from the concrete lid **3** just by removing the bolt **23** even in the case where the thermocouple **21** is deteriorated by radioactive rays, replacement work is simple when the temperature sensors **17**, **21** or **22** is out of order.

Additionally, in the case of the present embodiment, the bar-shaped thermometer **4** and the penetration hole **25** of the concrete lid **3** into which the thermometer **4** is inserted are both formed in tapered shapes, and have structures in which both peripheral surfaces closely contact each other in a state that the first temperature sensor **21** provided at the tip of the bar-shaped thermometer **4** is located close to the canister top portion $\mathbf{1}_T$ to an extent not contacting the canister top portion $\mathbf{1}_T$.

In this case, since the outer peripheral surface of the protection cylinder **24** of the bar-shaped thermometer **4** closely contacts an inner peripheral surface that defines the penetration hole **25**, an air layer is not formed between the concrete lid **3** and the bar-shaped thermometer **4** and a heat insulation effect is prevented from being generated. Therefore, the temperature of the concrete **16** of the bar-shaped thermometer **4** can follow temperature change inside the concrete **11** of the concrete lid **3**, and the temperature of the concrete **16** can be treated as the lid inner temperature T_{LM}.

Needless to mention, a relation between the bar-shaped thermometer **4** and the penetration hole **25** of the concrete lid **3** may be a relation between a straight bar and a straight through hole. Even in this case also, the temperature of the concrete **11** of the concrete lid **3** can be reflected on the concrete **16** of the bar-shaped thermometer **4** by closing clearance between the bar-shaped thermometer **4** and the concrete lid **3** by filling mortar and the like.

According to the experiments by the inventor, when helium leakage occurs from the inside of the canister **1**, the surface temperature T_T of the canister top portion $\mathbf{1}_T$ starts decreasing, and the inner temperature T_{LM} of the concrete lid **3** changes with a time lag from the change of the surface temperature T_T of the canister top portion $\mathbf{1}_T$ and also gradually decreases compared to a decrease rate of the surface temperature T_T of the canister top portion $\mathbf{1}_T$. Based on this fact, the inventor has found that: when helium leakage occurs from the inside of the canister **1**, a difference between the surface temperature T_T of the canister top portion $\mathbf{1}_T$ and the inner temperature T_{LM} of the concrete lid **3** changes; and this change tends to be enlarged.

Additionally, as described above, by measuring the temperature of the bottom portion **14** of the concrete lid **3** or the temperature of the member existing between the bottom portion **14** and the canister top portion $\mathbf{1}_T$ and receiving influence of the canister top portion temperature T_T, namely, the lid bottom portion temperature T_{LB}, even the thermocouple or the thermistor can measure a temperature having sufficiently high correlation with the surface temperature of the canister top portion $\mathbf{1}_T$ in a non-contacting state.

For example, it is found that the temperature T_{LB} of the metal plate **20** measured by the first temperature sensor **21** becomes almost same value as the canister top portion temperature T_T, namely $T_{LB} \approx T_T$, by setting, close to a position about 10 mm from the surface of the canister top portion $\mathbf{1}_T$, the first temperature sensor **21** adapted to measure the temperature of the metal plate **20** located at the tip of the bar-shaped thermometer **4**.

Accordingly, measured temperature data of the first temperature sensor **21** or **22** and the second temperature sensor **17** output from the temperature measurement device **26** are taken into, for example, the gas leakage estimation unit **31** formed inside an apparatus **30** that detects gas leakage, and change of the temperature difference between the lid inner temperature T_{LM} and the canister top portion temperature T_T is displayed on a display device **35** to enable comparison and monitoring. Alternatively, when there is significant fluctuation in the temperature difference, it is determined that leakage of the inactive gas is occurring, and a message indicating this fact is displayed, or various warning actions such as warning sound, warning light emission, and the like can be executed.

Here, decay heat of spent fuel inside the canister is reduced with passage of years, and therefore, the canister top portion temperature T_T decreases even without occurrence of inactive gas leakage. A decreased temperature of the canister top portion temperature T_T caused by reduction of decay heat with age (hereinafter referred to as decreased temperature T_d with age) is, for example, about 1° C. per year according to the experiments by the inventor. However, in the case where leakage is little, this may be a factor of detection error. Therefore, discriminating the factor is preferable.

Accordingly, preferably, the decreased temperature T_d with age caused by the reduction of decay heat is considered as an allowable value in the present invention.

Additionally, a maximum decreased temperature of the canister top portion temperature T_T caused by helium leakage (hereinafter referred to as maximum decreased temperature T_{Ld} at the time of gas leakage) also decreases along with decrease of the canister top portion temperature T_T caused by the reduction of decay heat.

Therefore, the apparatus for detecting gas leakage according to the present embodiment is adapted to consider reduction of decay heat caused by passage of storage period.

Here, the apparatus for detecting gas leakage may be formed by a dedicated device including respective units to execute predetermined processing, or may be implemented by a computer executing a program.

For example, in an example illustrated in FIG. **29**, a gas leakage detection program **39** stored in a storage unit **34** is executed, thereby implementing the apparatus for detecting gas leakage by a computer **30**. However, the apparatus for detecting gas leakage may also be formed as the dedicated device **30** including respective units such as a data receiving unit **31***a* and the like to execute predetermined processing, a display control unit **32**, and so on.

The apparatus for detecting gas leakage according to the present embodiment has the gas leakage estimation unit **31** that includes: a data receiving unit **31***a* adapted to read the canister top portion temperature T_T or the temperature T_{LB} of the member that receives influence of the canister top portion temperature T_T as a substitute temperature thereof, and the lid inner temperature T_{LM} from the temperature measurement device **26** including the first temperature sensor **21** and the second temperature sensor **17**; a Ts determination unit **31***b* adapted to calculate a threshold temperature Ts to determine occurrence of gas leakage; a reference temperature determination unit **31***c* adapted to determine, as reference temperatures, average values of respective measured temperatures or temperatures at certain time points at the time or during a period deemed as a proper operation state without gas leakage; a change amount calculation unit **31***d* adapted to calculate differences δT_T or δT_{LB}, and δT_{LM} from the respective reference temperatures of the respective measured temperatures (hereinafter referred to as change amounts of the measured temperatures); a change amount monitoring unit **31***e* adapted to calculate and monitor a difference $\delta(T_{LM}-T_T)$ or a difference $\delta(T_{LM}-T_{LB})$ between change amounts of the measured temperatures from the reference temperatures (hereinafter referred to as difference between change amounts); and a gas leakage determination unit **31***f* adapted to determine occurrence of gas leakage when the difference between change amounts $\delta(T_{LM}-T_T)$ or $\delta(T_{LM}-T_{LB})$ is larger than the threshold temperature Ts.

Meanwhile, in the present embodiment, exemplified is the case of adopting the lid bottom portion temperature T_{LB} as the substitute temperature of the canister top portion temperature T_T because the temperature at the tip of the bar-shaped thermometer **4** set closest to the canister top portion $\mathbf{1}_T$, specifically, the lid bottom portion temperature T_{LB} measured by the first temperature sensor **21** in FIG. **2** is almost the same value as the canister top portion temperature T_T. In this point, the above-described and the mentioned below canister top portion temperature T_T may also be described as the lid bottom portion temperature T_{LB}.

However, in the case of directly measuring the canister top portion temperature T_T itself with a non-contact type temperature sensor or the like, this temperature may also be used. Furthermore, even when the canister top portion temperature T_T and the lid bottom portion temperature T_{LB}, are not almost the same values, in the case where there is high correlation between both temperatures, the lid bottom portion temperature T_{LB} may also be used.

Additionally, the apparatus for detecting gas leakage according to the present embodiment includes the display control unit **32** adapted to constantly display, on the display device **35**, the change amounts δT_{LM} and δT_T from the respective reference temperatures of the respective measured temperatures and/or fluctuation of a change amount difference therebetween $\delta(T_{LM}-T_T)$. Note that reference sign **33** in the drawing indicates a control unit (central processing device), reference sign **36** a warning device, reference sign **37** an input unit, and reference sign **38** a memory respectively.

Ts determination unit **31***b* calculates the maximum decreased temperature T_{Ld} at the time of gas leakage and the decreased temperature T_d with age, and determines the threshold temperature Ts adapted to determine occurrence of gas leakage within a range between the maximum decreased temperature T_{Ld} at the time of gas leakage and the decreased temperature T_d with age. In other words, the threshold temperature Ts is an index in order to determine whether a difference between the canister top portion temperature T_T and the inner temperature T_{LM} or a difference between the lid bottom portion temperature T_{LB} and the inner temperature T_{LM} indicates significant fluctuation.

In the case where the threshold temperature Ts is set to a value close to, for example, the decreased temperature T_d with age, the value is included in a fluctuation band in normal operation time, and this may cause a determination error such as leakage occurrence in spite of a fact that inactive gas is not actually leaking. On the other hand, in the case where the threshold temperature Ts is set to a value close to, for example, the maximum decreased temperature T_{Ld} at the time of gas leakage, there may be a concern that abnormality is overlooked. Therefore, the threshold temperature Ts is preferably set to a temperature lower than the maximum decreased temperature T_{Ld} at the time of gas leakage and higher than the decreased temperature T_d with age, for example, an intermediate value therebetween or a value close the intermediate value.

Here, the maximum decreased temperature T_{Ld} at the time of gas leakage is attributable to a phenomenon caused by convection change inside the canister at the time of leakage. Therefore, it is not easy to calculate the maximum decreased temperature T_{Ld} at the time of gas leakage because calculation is complicated. Accordingly, a database for test results accumulated in heat removal tests and leakage tests per concrete cask type may be preliminarily prepared, and the threshold temperature Ts may also be determined by calculating an optimal temperature based on the database. Needless to mention, the maximum decreased temperature T_{Ld} at the time of gas leakage may also be acquired by calculation.

For example, the maximum decreased temperature T_{Ld} at the time of gas leakage and the decreased temperature T_d with age can be estimated from decay heat analysis results and test results.

In the case where a storage period and a stored fuel kind are known, a heat generation amount, namely, an amount of decay heat can be calculated by using an analysis code. Therefore, a heat generation amount can be obtained by calculating the decay heat in accordance with the storage period. According to a heat removal experiment using a full-scale concrete cask model and performed simulating the above-described heat generation amount with a heater, for example, the canister top portion temperature T_T in a CFS cask (Case 1) is 162.3° C. when the storage period is zero years, 134.9° C. when the storage period is 20 years, and 106.4° C. the storage period is 40 years as illustrated in FIG. **35**. According to this, the canister top portion temperature T_T decreases at a rate of 1.37° C. per year until 20 years and at a rate of 1.425° C. per year until 40 years.

In other words, when a kind of stored fuel is known, the heat generation amount can be obtained by calculating the decay heat in accordance with the storage period. Furthermore, an estimation value of the decreased temperature T_d with age in accordance with the years of storage can be calculated by proportional calculation with a calculated heat generation amount and the test data corresponding to the concrete cask type of a monitoring target.

As for the maximum decreased temperature T_{Ld} at the time of gas leakage, when a gas leakage test using a full-scale cask model is performed for each of the concrete casks of Cases 1 to 3 relative to zero years of storage (22.6 kW), an estimation value of the maximum decreased temperature T_{Ld} at the time of gas leakage in accordance with the years of storage can be calculated by the proportional calculation. For example, in the case of the CFS cask having pressure decrease of 0.5 atm (Case 1), the maximum decreased temperature T_{Ld} at the time of gas leakage is 6° C. when the storage period is zero years (22.6 kW). Therefore, since the years of storage, namely, the heat generation amount and canister temperature distribution are similar, in the case of executing proportional calculation, the estimation value becomes 5.4° C. when the storage period is 20 years (16 kW) and becomes 4.2° C. when the storage period is 40 (10 kW).

Additionally, the threshold temperature Ts is determined considering balance between, for example, the maximum decreased temperature T_{Ld} at the time of gas leakage and determination of an error range based on data accumulation by monitoring during the proper operation time without occurrence of gas leakage. Simultaneously, the threshold temperature Ts is a physical amount, in other words, a physical quantity/a physical value, influenced by an installation position because a temperature value to be detected is varied by how close to the canister top portion $\mathbf{1}_T$ the first temperature sensor **21** or **22** can be installed.

In the case where the first temperature sensor **21** can be set closest to the canister top portion $\mathbf{1}_T$ like the bar-shaped thermometer illustrated in FIG. **2**, the threshold temperature Ts may be calculated by following arithmetic processing: [threshold temperature Ts=(maximum decreased temperature T_{Ld} at the time of gas leakage)/2]. Needless to mention, the maximum decreased temperature T_{Ld} at the time of gas leakage becomes a little low because the lid bottom portion temperature T_{LB} is measured at a position distant from the canister top portion $\mathbf{1}_T$, and influence of the decreased temperature T_d with age cannot be ignored. Therefore, preferably, the threshold temperature Ts is calculated as: [threshold temperature Ts=(maximum decreased temperature T_{Ld} at the time of gas leakage−decreased temperature T_d with age)/2].

For example, in the case of the CFS cask in Case 1 in which the maximum decreased temperature T_{Ld} at the time of gas leakage is 6° C. and the decreased temperature T_d with age is about 1° C. per year, according to an example of FIG. **32** in which the first temperature sensor **21** is set closest to the canister top portion $\mathbf{1}_T$, about 3 to 4° C. may be considered to be an appropriate setting value. According to an example of FIG. **34** in which the temperature T_{LB} of the member that receives influence of the canister top portion temperature T_T and is separated from the canister top portion $\mathbf{1}_T$ is measured, about 2 to 3° C. may be considered to be an appropriate setting value. Meanwhile, it is appropriate to set the decreased temperature T_d with age to 1° C. and set a data review period t_0 to one year.

Furthermore, the maximum decreased temperature T_{Ld} at the time of gas leakage is largely influenced by change of inner pressure according to the gas leakage tests executed by the inventor. Additionally, since the amounts of decay heat is reduced in the maximum decreased temperature T_{Ld} at the time of gas leakage and the decreased temperature T_d with age with passage of the storage period, the temperatures tend to decrease even without occurrence of helium leakage.

In other words, since the maximum decreased temperature T_{Ld} at the time of gas leakage is varied by change of the inner pressure and the amount of decay heat, it is not preferable to fix the threshold temperature Ts depending on circumstances. Therefore, preferably, the data review period t_0 is set, and the decreased temperature T_d with age at the canister top portion is reviewed and the threshold temperature Ts to determine gas leakage is recalculated and determined every time the review period t_0 elapses.

Meanwhile, there is published data related to transition of temperature distribution of the respective portion and the like from beginning of storage to end of storage in a cask made of RC or a cask made of CFS. Therefore, the decreased temperature T_d with age that may occur during the data review period t_0 can be easily determined based on such published heat removal test results in the casks.

In the following, a processing procedure in the apparatus for detecting gas leakage according to the present embodiment will be described based on a flowchart illustrated in FIG. **30**.

First, the canister top portion temperature T_T and the lid inner temperature T_{LM} detected by the first and second temperature sensors **21**, **17** are read from the temperature measurement device **26** (Step **101**).

Next, the threshold temperature Ts to determine occurrence of gas leakage is calculated (Step **102**). In the present embodiment, the threshold temperature Ts is suitably determined within a range from the maximum decreased temperature T_{Ld} at the time of gas leakage or less and the decreased temperature T_d with age or more after acquiring the maximum decreased temperature T_{Ld} at the time of gas leakage and the decreased temperature T_d with age at the canister top portion which are observed during the data review period t_0. For example, the threshold temperature Ts is calculated by Expression 1 or Expression 2 as shown below.

$$Ts=T_{Ld}/2 \qquad \text{[Expression 1]}$$

$$Ts=(T_{Ld}-T_d)/2 \qquad \text{[Expression 2]}$$

As just an example of the threshold temperature Ts, specifically, a value such as 3° C. or 2.5° C. is calculated in the case of the CFS cask in Case 1. Since the maximum decreased temperature T_{Ld} at the time of gas leakage and the decreased temperature T_d with age at the canister top portion are varied by the inner pressure of the canister and the heat generation amount, these temperatures are estimated from the data review period t_0 and knowledge achieved by calculation and past tests.

The data review period t_0 is not limited to a specific period, and suitably set considering magnitude of change assumed for the maximum decreased temperature T_{Ld} at the time of gas leakage and the decreased temperature T_d with age. As just an example of the data review period t_0, specifically, one year or two years may be exemplified.

Next, a reference temperature is determined. The reference temperature is an average value of each of the two temperatures T_T and T_{LM} during a period reference temperature without occurrence of helium leakage or a temperature at a certain time point during the proper operation time (Step **103**).

The temperatures such as the canister top portion temperature T_T and the lid inner temperature T_{LM} are considered to keep a constant temperature difference and fluctuate in a long cycle unless otherwise gas leakage occurs. Therefore, an appropriate time during monitoring is determined, and each of temperatures at this time may be determined as a reference point. The time is optional, and in the present embodiment, for example, a value of −96 hours is adopted, but the time does not mean anything special.

The differences between the reference temperatures T_{T0} and T_{LM0} and the respective measured temperatures T_T and T_{LM}, namely, the change amounts of the respective measured temperatures δT_T and δT_{LM} are calculated and set as monitoring data (Step **104**).

Additionally, a difference $\delta(T_{LM}-T_T)$ between the temperature change amounts δT_T and δT_{LM} from the respective reference temperatures T_{T0} and T_{LM0} is calculated and monitored (Step **105**).

Next, as quantitative determination, whether $Ts<\delta(T_{LM}-T_T)$ is satisfied is constantly monitored (Step **106**). In the case where the above relation is satisfied, whether such a relation is a temporary phenomenon like noise is checked (Step **107**).

Whether noise or not is determined by, for example, whether there is a predetermined temperature difference compared to previous and former data in the case where noticeable data is observed. Specifically, when there is the predetermined temperature difference, it is determined as noise. Since noise can be removed also by changing a sampling time, Step **107** is not needed in this case.

Furthermore, in monitoring by the display device **35**, the noticeable data shaped like a whisker as illustrated in the graphs of FIG. **31** or **33** can be easily determined as noise.

when not determined as noise, it is determined as leakage (Step **108**).

In this case, a warning sound, a warning message, and the like are output to the warning device **36** or the display device **35** (Steps **110** and **111**).

On the other hand, in the case where $Ts<\delta(T_{LM}-T_T)$ is not satisfied or in the case where data is determined as noise although the relation is satisfied, whether a monitoring period t is longer than the data review period t_0 is checked (Step **109**).

In the case where the monitoring period t is shorter than data review period t_0, it is determined as "No Abnormality", and the process returns to the processing in Step **104** and monitoring is continued.

On the other hand, in the case where the monitoring period t is longer than the data review period t_0, the process returns to the processing in Step **102**, and the setting values (Ts, Td) are reviewed again (Step **102**). Then, the reference values of the respective temperatures (T_{T0}, T_{LM0}) are reviewed (Step **103**), and monitoring is continued (Step **104**).

In other words, after the data review period t_0 passes, the decreased temperature T_d with age at the canister top portion is estimated in accordance with years of storage by using the decay heat analysis results and test results, and the threshold temperature Ts to determine occurrence of gas leakage based on the decreased temperature T_d with age is calculated and newly set (Step **102**).

Meanwhile, as a gas leakage detection system, leakage may be determined by whether the temperature difference to be monitored by a computer is significant fluctuation or not. When the condition is satisfied, only an alarm may be issued, but as a safe measure as the detection system, real time monitoring for temperature in time-series is preferably provided in terms of confirming no abnormality.

Needless to mention, determination on presence of gas leakage can be easily made by a worker even without using the computer **30** if only the temperature changes of the lid inner temperature T_{LM} and the canister top portion temperature T_T or change of the temperature difference between these temperatures are displayed on the display device **35**.

In other words, as described above as the characteristics found by the inventor, in the event of helium leakage from the inside of the canister **1**, change is generated in the difference between the canister top portion temperature T_T or the lid bottom portion temperature T_{LB} and the lid inner temperature T_{LM}, and the change tends to be enlarged.

Judging from this, only by comparatively displaying, on the display device **35**, the temperature changes of the lid inner temperature T_{LM} and the canister top portion temperature T_T or the lid bottom portion temperature T_{LB}, a monitoring person can visually and intuitively determine that a phenomenon different from normal operation time is occurring, and can estimate helium leakage.

For example, it may be considered that differences between respective temperatures at the measurement time and the respective average temperatures of the two temperatures during a period deemed as proper operation time without occurrence of helium leakage or respective temperatures of the two temperatures at a specific time point during the proper operation time (referred to as the reference temperature) are respectively calculated as change amounts, and additionally, a difference between these change amounts is acquired and monitored. In this case, when the difference between the temperature change amounts tends to increase, it can be determined that leakage is occurring.

Furthermore, in the case of directly comparing actual measurement temperatures of the two temperatures T_T and T_{LM} or actual measurement temperatures of the temperatures T_{LB} and T_{LM}, when the temperature difference between both temperatures tends to be reduced, it can be determined that leakage is occurring. Furthermore, in the case of displaying two actual measurement temperatures to be compared also, the two actual measurement temperatures are multiply displayed, making the respective comparing average values of the two actual measurement temperatures the same. Consequently, when a deviation state in a graph illustrating changes of temperatures of both temperatures tends to be enlarged, it can be determined that leakage is occurring.

For example, as illustrated in FIGS. **14**, **17**, and **18**, in the case of constantly displaying temperature change between the lid inner temperature T_{LM} and the canister top portion temperature T_T or the lid bottom portion temperature T_{LB} (or T_{LBI}) on the display device in time series, the temperature change between the canister top portion temperature T_T or the lid bottom portion temperature T_{LB} (or T_{LBI}) and the lid inner temperature T_{LM} can be monitored and compared. Therefore, in the case where deviation is generated in the graph of these temperatures and the deviation tends to be enlarged, namely, in the case where the difference between the two temperatures (relative difference) tends to be enlarged, it can be determined that helium leakage is occurring.

Here, as illustrated in FIGS. **23** and **26**, when display of the lid inner temperature T_{LM} and the canister top portion temperature T_T or display of the lid inner temperature T_{LM} and the lid bottom portion temperature T_{LB} are multiply displayed making the average values of the respective measurement amounts the same, it is possible to visually intuitively and easily grasp a tendency, as the deviation state of a plurality of graphs, in which a differences between the two temperatures (relative difference) is enlarged.

Furthermore, a display method of temperature data to be monitored on the display device **35** is not limited the above-described method. For example, preferably, presence of leakage can be estimated or can be determined by displaying, monitoring, and comparing, as illustrated in FIG. **31**, the temperature change amounts δT_{LM} and δT_T from the respective reference temperatures at the canister top portion temperature T_T and the lid inner temperature T_{LM} in time series at the same time.

In this case, in the event of helium leakage, the deviation state generated between both temperatures changes can be more easily and visually grasped.

Furthermore, it may also be possible to read intermediate temperature data between the lid inner temperature T_{LM} and the temperature at the tip of the bar-shaped thermometer set closest to the canister top portion, substituted as the canister top portion temperature T_T (temperature of the first temperature sensor **21**), such as the temperature T_{LB} of the metal plate **14** of the concrete lid bottom portion, and monitor temperature differences (δT_T, δT_{LB}, δT_{LM}) between the respective reference temperatures and the respective temperatures (T_T, T_{LB}, T_{LM}) (refer to FIG. **33**).

In this case, when helium leakage occurs from the inside of the canister **1**, the deviation state in which obvious differences are generated between the temperatures at the three points, namely, a phenomenon in which time lag according to an influence level of the canister top portion temperature is generated in temperature change of the canister top portion temperature T_T is significantly observed. Therefore, it is possible to easily and visually grasp the temperature change as a significant fluctuation.

Additionally, for example, as illustrated in FIG. **24**, **27**, or **32**, in the case of constantly displaying, on the display device **35**, the difference of change amounts of the measured temperatures $\delta(T_{LM}-T_T)$ or $\delta(T_{LM}-T_{LB})$ between the lid inner temperature T_{LM} and the canister top portion temperature T_T or the lid bottom portion temperature T_{LB} in time series, it is possible to easily and visually grasp occurrence of leakage because the value of $\delta(T_{LM}-T_{LB})$ shows rising movement when helium leakage occurs from the inside of the canister **1**.

Furthermore, as illustrated in FIGS. **25**, **28**, and **34**, in the case of displaying, on the display device **35**, the differences of the temperature change amounts $\delta(T_{LM}-T_T)$ and $\delta(T_{LM}-T_{LB})$ between the lid inner temperature T_{LM} and the canister top portion temperature T_T and between the lid inner temperature T_{LM} and the lid bottom portion temperature T_{LB} from the respective reference temperatures in time series, it is possible to easily and visually grasp occurrence of leakage because the values of $\delta(T_{LM}-T_T)$ and $\delta(T_{LM}-T_{LB})$ show rising movement with time lag when helium leakage occurs. Both $(T_{LM}-T_T)$ and $\delta(T_{LM}-T_{LB})$ start rising from zero hours after start of helium leakage, and temperature movement in which a temperature difference between both temperature is generated can be monitored in 24 hours. Therefore, it is possible to visually and intuitively determine that a phenomenon obviously different from normal operation time is occurring (temperature difference is having significant fluctuation).

Normally, as illustrated in FIG. **31** or **33**, time variation (time variation of differences) of the temperature change amounts δT_{LM}, δT_T, and/or δT_{LB} from the respective reference temperatures of the above-described lid inner temperature T_{LM} and canister top portion temperature T_T and/or lid bottom portion temperature T_{LB} are displayed and compared on the display device **35**, and is made available for monitoring as an item of daily inspection work of a worker. When a difference is observed between the respective temperature change amounts in such monitoring, a screen display is switched to the display in FIG. **32** or **34** and an amount of the difference is confirmed.

Meanwhile, displaying measured temperature change is a function which can be implemented by using a monitor of an existing data logger without relying on particular arithmetic processing by a computer, and also such a display can be easily achieved by installing software bundled with the data logger in a personal computer. Additionally, switching screen display is a general function which can be easily executed by using a commercially available data logger monitor or by the software bundled to the data logger and installed in the personal computer.

Meanwhile, the above-described embodiment is an example of preferable implementation of the present invention, but the present invention is not limited thereto, and various modifications can be made within a scope without departing from the gist of the present invention.

For example, in the present embodiment, the description has been mainly provided for the example of inserting the bar-shaped thermometer **4** including the second temperature sensor **17** and the first temperature sensor **21** or **22** into the penetration hole **25** opened at the concrete lid **3**, but not limited thereto, there may be another possible manufacture in which a thermocouple is preliminarily embedded inside the concrete **11** at the time of manufacturing the concrete lid **3** and a wire is preliminarily led to the outside after pasting the thermocouple on a front surface or a back surface facing the canister top portion of the metal plate **14** at the bottom portion. Needless to mention, a temperature may also be measured at a place close to the canister top portion $\mathbf{1}_T$ by making a portion of the metal plate **14** of the bottom portion of the concrete lid **3** project to the vicinity of the canister top portion $\mathbf{1}_T$.

In the following, a description will be provided for matters and results of experiments that support effectiveness of the method and apparatus for detecting gas leakage from radioactive material sealed container according to the present invention.

<Experiments>

(1) Helium Leakage Test Conditions

Helium leakage tests from a canister were performed using a full-scale concrete cask model. The cask structures used in the leakage tests are illustrated in FIGS. **4A**, **4B**, and **4C**. Additionally, test conditions are described in Table 1.

TABLE 1

CASE No.	Cask Structure	Inner Pressure Before Leakage (kPa)	Leakage Rate (Pa · m³/s)
CASE 1	CFS	56	4.86×10^{-1}
CASE 2	CFS (Lid having outlet ducts with low flow resistance)	151	5.16
CASE 3	RC	59	3.60×10

<Case 1>

An openable/closable valve (not illustrated) was provided at a canister **1** of a concrete cask having a CFS structure illustrated in FIG. **4A**, an electric heater (not illustrated) simulating a nuclear reactor spent fuel rod was housed inside the canister **1** under the same conditions as an actual spent fuel rod, and helium was filled at an atmospheric level (0 kPa in gauge pressure). Thus, an initial storage state of spent nuclear fuel was simulated in the concrete cask (heat generation amount 22.6 kW).

Inner pressure of the canister **1** rose by heat generation of the electric heater, and a steady state was obtained at gauge pressure 56 kPa. After that, the canister top portion temperature T_T, canister bottom portion temperature T_B, feeding air temperature T_{IN}, lid bottom portion temperature T_{LB}, concrete lid upper portion temperature T_{LT}, lid inner temperature T_{LM}, and an air temperature T_{LA} between the concrete lid bottom portion and the canister top portion were continuously measured by the thermocouple provided at each of seven measurement points illustrated in FIG. **4A**.

Then, subsequently, helium was made to leak rapidly by loosening the valve provided at the canister **1**, and pressure was reduced by 50 kPa in two days, and the inner pressure of the canister **1** was reduced to become nearly the atmospheric pressure level four days later. Meanwhile, an amount of decay heat was calculated by an analysis code.

<Case 2>

Additionally, helium was also filled same as above in a canister **1** of a concrete cask having a CFS structure using a lid having outlet ducts with low flow resistance illustrated in FIG. **4B**, and inner pressure of the canister **1** was raised and a steady state was obtained at gauge pressure 151 kPa. Then, temperatures at seven measurement points illustrated in FIG. **4B** were continuously measured in the same manner as Case 1.

The inner pressure of the canister **1** was reduced to a nearly atmospheric pressure level in about one day by rapidly leaking helium.

<Case 3>

Additionally, helium was also filled same as above in a canister **1** of a concrete cask having an RC structure having an air inlet port shaped differently from Cases 1 and 2 illustrated in FIG. **4C**, and inner pressure of the canister **1** was raised and a steady state was obtained at gauge pressure 59 kPa. Then, temperatures at seven measurement points illustrated in FIG. **4C** were continuously measured in the same manner as Case 1.

The inner pressure of the canister **1** was reduced by rapidly leaking helium so as to become nearly the atmospheric pressure level in about two to three hours.

(2) Helium Leakage Test Results

Temperature measurement results at the respective measurement points are illustrated in FIGS. **5** to **28**.

(i) First, in FIGS. **5** to **10**, a relation of the canister top portion temperature T_T and the canister bottom portion temperature T_B with the inner pressure inside canister **1** and a relation of the canister top portion temperature T_T and the canister bottom portion temperature T_B with the feeding air temperature T_{IN} in Cases 1 to 3 will be described. In all of Cases, the canister top portion temperature T_T decreased and the canister bottom portion temperature T_B rose immediately after helium leakage (zero seconds is leakage start time) (refer to FIGS. **5**, **7**, and **9**).

Furthermore, it has been found that the bottom portion of the canister **1** was largely influenced by external air/cooling air flowing from the air inlet port **7**, and the canister bottom portion temperature T_B changed following daily fluctuation of the feeding air temperature T_{IN} (refer to FIGS. **6**, **8**, and **10**).

On the other hand, it has been found that the canister top portion $\mathbf{1}_T$ in Cases 1 and 2 received influence of long-term temperature fluctuation of the external air **5** in about a five-day cycle but did not receive influence of daily fluctuation because a space between the concrete lid **3** and the canister **1** was narrow and high-temperature air stagnated (refer to FIGS. **6** and **8**).

This implies that a temperature difference between the canister top portion temperature T_T and the canister bottom portion temperature T_B causes daily fluctuation by receiving influence of the feeding air temperature T_{IN}. Additionally, even in the case of having different structures of the concrete cask, to one degree or another, the same tendency was observed.

Meanwhile, in Case 2 in which the inner pressure of helium was made high, influence of helium leakage/pressure change given to the canister top portion temperature T_T and the canister bottom portion temperature T_B was large, and a significant gap of the temperature difference between the canister top portion temperature T_T and the canister bottom portion temperature T_B was observed.

(ii) On the other hand, FIGS. **11** to **16** illustrate a relation between change of the canister inner pressure and change of the canister top portion temperature T_T and a relation between the canister top portion temperature T_T and temperatures at other positions before and after helium leakage (zero seconds is leakage start time) in Case 1.

First, the relation between the canister top portion temperature T_T and the inner pressure of the canister **1** has a relation in which both decrease immediately after helium leakage (refer to FIG. **11**). Furthermore, the air temperature T_{LA} between the concrete lid bottom portion and the canister top portion receives influence of temperature fluctuation of the external air (refer to FIG. **12**).

Furthermore, the canister top portion temperature T_T receive neither influence of fluctuation of the feeding air temperature T_{IN} (refer to FIG. **16**) nor influence of temperature fluctuation of the concrete lid upper portion temperature T_{LT} (refer to FIG. **15**).

Furthermore, it is obvious that the concrete lid upper portion temperature T_{LT} receives influence of temperature fluctuation of the external air (refer to FIG. **15**), and the lid inner temperature T_{LM} and the lid bottom portion temperature T_{LB} do not receive much influence of the external air (refer to FIGS. **14** and **13**).

Additionally, it is found that the lid bottom portion temperature T_{LB} sensitively follows the canister top portion temperature T_T even after leakage has started although there is some time lag (refer to FIG. **13**), and the lid inner temperature T_{LM} insensitively follows the canister top portion temperature T_T (refer to FIG. **14**).

In other words, it is found that both the lid bottom portion temperature T_{LB} and the lid inner temperature T_{LM} each keep a constant temperature difference during normal operation time without occurrence of helium leakage, but in the event of helium leakage, the lid bottom portion temperature T_{LB} decreases while the lid inner temperature T_{LM} does not decrease. It is estimated that this is caused by the fact that the lid bottom portion temperature T_{LB} follows the canister top portion temperature T_T while the lid inner temperature T_{LM} does not follow the canister top portion temperature T_T.

Meanwhile, in the present experiments, a temperature at the center of the canister top portion $\mathbf{1}_T$ where temperature change is maximum is adopted as the canister top portion temperature T_T. Since the temperature change of the canister top portion temperature T_T caused by helium leakage at the center portion thereof is maximum, this temperature change is optimal for detecting helium leakage, but not limited to the temperature change at the center portion, temperature change at a peripheral region distant from the center of the canister **1** and the concrete lid **3** may also be used depending on circumstances.

Based on the above experiments results, it is found that helium leakage information can be detected by comparing the temperature change between the lid bottom portion temperature T_{LB} and the lid inner temperature T_{LM}. In other words, as illustrated in FIG. **17**, a factor of increasing the temperature difference between both temperatures is estimated to be helium leakage from the canister **1**. This tendency was also observed in Case 3 in which the cask having a different-shape flow passage as illustrated in FIG. **18**.

In other words, it is found that it can be estimated that helium leaks from the canister by monitoring and comparing the lid bottom portion temperature T_{LB} and the lid inner temperature T_{LM} in the case where the temperature difference between both temperatures is increased (the temperature difference is significant fluctuation).

(3) Understanding Phenomenon Based on Analysis

In order to study temperature change from the canister top portion $\mathbf{1}_T$ to the concrete lid upper portion, non-constant one dimensional thermal conduction analysis was performed at the respective measurement points illustrated in FIG. **3**. Meanwhile, as illustrated in FIG. **19**, as for boundary conditions, the canister top portion temperature T_T is set to linearly lower by 7° C. from 158° C. to 151° C. in 96 hours (four days) from leakage start (zero hours) while the concrete lid upper portion air temperature T_{TA} is provided with a temperature condition that is daily fluctuation in a 24-hour cycle with a fluctuation width of ±3° C. at an average temperature 30° C.

Analysis results are illustrated in FIGS. **20** and **21**. From the analysis results, it is found that there is little temperature difference in a range of 200 mm to 800 mm from the upper surface of the canister, namely, inside the concrete **11** of the concrete lid. Therefore, any portion inside the concrete **11** may be suitable to be treated as the lid inner temperature T_{LM}.

Additionally, as illustrated in FIG. **22**, influence of the temperature fluctuation of the concrete lid upper portion air temperature T_{TA} was observed in the concrete lid upper portion temperature T_{LT}, and also slight temperature decrease was observed after gas leakage start.

Furthermore, as illustrated in FIG. **23**, according to the relation between the lid bottom portion temperature T_{LB} and the lid inner temperature T_{LM}, same as the tendency observed in the tests, the lid bottom portion temperature T_{LB} quickly followed fluctuation of the canister top portion temperature T_T after gas leakage start while the lid inner temperature T_{LM} insensitively followed the canister top portion temperature T_T, and a relative difference was generated between both temperatures.

Therefore, as illustrated in FIG. **24**, when the value of $\delta(T_{LM}-T_{LB})$ is increased by monitoring and comparing the difference from the average value of the lid bottom portion temperature T_{LB} and the difference from the average value of the lid inner temperature T_{LM}, it can be determined that leakage is occurring based on the fact that there is the significant fluctuation in the temperature differences.

Additionally, FIG. **25** illustrates comparison between $\delta(T_{LM}-T_{LB})$ and $\delta(T_{LM}-T_T)$. Judging from the results, it can be considered that the more the temperature information of the lid bottom portion temperature T_{LB} close to the canister top portion temperature T_T can be obtained, the more the detection sensitivity can be improved.

(4) Study on Improving Detection Sensitivity

Considering above, the inventor of the present invention made study on measurement positions by the one dimensional heat conduction analysis in order to obtain a setting position, namely, a measurement position of the first temperature sensor **21** at which higher sensitivity can be achieved.

In order to make the lid bottom portion temperature T_{LB} closest to the temperature of the canister top portion temperature T_T under the same analysis input conditions, a distance between the measurement position of the lid bottom portion temperature T_{LB} and the canister top portion $\mathbf{1}_T$ was set from 67 mm in FIG. **3** to 10 mm as illustrated in FIG. **2**, and furthermore, a thickness of a glass wool **19** to the lower portion of the concrete was increased.

As a result, as illustrated in FIG. **28**, it has been found that the lid bottom portion temperature T_{LB} became a value almost same as the canister top portion temperature T_T. Judging from this fact, it can be considered that temperature information close to the canister top portion temperature T_T can be obtained by setting the measurement point of the lid bottom portion temperature T_{LB} close to the canister top portion $\mathbf{1}_T$, and highly sensitive leakage detection can be achieved.

Furthermore, in the experiments, the metallic protection cover **20** formed of a metal plate having a thickness of 5 mm was provided at the tip of the bar-shaped thermometer **4**. Additionally, the thermocouple **22** as the first temperature sensor was provided on a surface on the opposite of the surface facing the back surface of the metal plate **20**, namely, the canister top portion $\mathbf{1}_T$, and the back surface temperature T_{LBI} at the lid bottom portion was measured. Since the metal plate **20** has high heat conductivity, it is found that the lid bottom portion temperature T_{LB} and the back surface temperature T_{LBI} of the metal plate at the lid bottom portion become almost the same values also from the result illustrated in FIG. **26**.

Therefore, it is found that γ-rays may be prevented from directly being received from the canister top portion by arranging the thermocouple **22** on the back side of the metal plate **20** as the member that receives influence of the canister top portion temperature T_T and measuring the back surface temperature T_{LBI} of the metal plate.

What is claimed is:

1. A method for detecting gas leakage from a radioactive material sealed container, adapted to detect leakage of inactive gas from a metallic sealed container of the radioactive material sealed container that includes: the metallic sealed container configured to store and seal spent fuel and the inactive gas; and a non-sealed concrete-made storage container having a shielding function and configured to store the metallic sealed container, the method comprising:

measuring a temperature at a top portion of the metallic sealed container, a temperature at a bottom portion of a lid portion of the concrete-made storage container facing the top portion of the metallic sealed container, or a temperature of a member existing between the bottom portion of the lid portion and the top portion of the metallic sealed container;

also measuring an inner temperature of the lid portion of the concrete-made storage container; and

estimating presence of leakage of the inactive gas by comparing the temperature at the top portion of the metallic sealed container with the inner temperature of the lid portion of the concrete-made storage container or comparing the inner temperature of the lid portion of the concrete-made storage container with the temperature at the bottom portion of the lid portion of the concrete-made storage container or the temperature of the member existing between the bottom portion of the lid portion and the top portion of the metallic sealed container.

2. The method for detecting gas leakage from a radioactive material sealed container according to claim **1**, wherein a difference between the temperature at the top portion of the metallic sealed container and the inner temperature of the lid portion of the concrete-made storage container, or a difference between the temperature at the bottom portion of the lid portion of the concrete-made storage container or the temperature of the member existing between the bottom portion of the lid portion and the top portion of the metallic sealed container and the inner temperature of the lid portion of the concrete-made storage container is displayed in time series.

3. The method for detecting gas leakage from a radioactive material sealed container according to claim **1**, wherein a temperature on a bottom surface of the lid portion of the concrete-made storage container is measured as the temperature at the bottom portion of the lid portion of the concrete-made storage container.

4. The method for detecting gas leakage from a radioactive material sealed container according to claim **1**, wherein a temperature of a metal plate arranged at a position closer to the top portion of the metallic sealed container than the bottom surface of the lid portion of the concrete-made storage container is measured as the temperature of the member existing between the bottom portion of the lid portion of the concrete-made storage container and the top portion of the metallic sealed container.

5. An apparatus for detecting gas leakage from a radioactive material sealed container, adapted to detect leakage of inactive gas from a metallic sealed container of the radioactive material sealed container that includes: the metallic sealed container configured to store and seal spent fuel and the inactive gas; and a non-sealed concrete-made storage container having a shielding function and configured to store the metallic sealed container, the apparatus comprising:

a first temperature sensor configured to measure a temperature at a top portion of the metallic sealed container, a temperature at a bottom portion of a lid portion of the concrete-made storage container facing the top portion of the metallic sealed container, or a temperature of a member existing between the bottom portion of the lid portion and the top portion of the metallic sealed container;

a second temperature sensor configured to measure an inner temperature of the lid portion of the concrete-made storage container; and a gas leakage estimation unit configured to estimate presence of leakage of the inactive gas by comparing a temperature measured by the first temperature sensor with a temperature measured by the second temperature sensor.

6. The apparatus for detecting gas leakage from a radioactive material sealed container according to claim **5**, further comprising a display device configured to display, in time series, a temperature difference between a temperature measured by the first temperature sensor and a temperature measured by the second temperature sensor.

7. The apparatus for detecting gas leakage from a radioactive material sealed container according to claim **5**, wherein the first temperature sensor measures a temperature at the bottom portion of the lid portion of the concrete-made storage container.

8. The apparatus for detecting gas leakage from a radioactive material sealed container according to claim **5**, wherein the first temperature sensor measures a temperature of a metal plate projecting toward the top portion of the metallic sealed container from a bottom surface of the lid portion of the concrete-made storage container and arranged at a position close to the top portion of the metallic sealed container.

9. The apparatus for detecting gas leakage from a radioactive material sealed container according to claim **8**, wherein the first temperature sensor is arranged interposing the metal plate in a space with the top portion of the metallic sealed container by being provided on a back surface of the metal plate arranged at a position close to the top portion of the metallic sealed container, and is configured to measure a temperature of the back surface of the metal plate.

10. The apparatus for detecting gas leakage from a radioactive material sealed container according to claim **5**, wherein the second temperature sensor measures a temperature of a concrete layer of the lid portion of the concrete-made storage container.

11. The apparatus for detecting gas leakage from a radioactive material sealed container according to claim **5**, wherein the first temperature sensor and the second temperature sensor are arranged in a vicinity of a center position in a planar view of the lid portion of the concrete-made storage container and the top portion of the metallic sealed container.

12. The apparatus for detecting gas leakage from a radioactive material sealed container according to claim **5**, wherein

the first temperature sensor and the second temperature sensor are thermocouples or thermistors, each held by a sensor holder having a shielding structure similar to the lid portion of the concrete-made storage container, and constitute a bar-shaped thermometer in which the first temperature sensor is provided on a surface of a metal plate at a tip portion and the second temperature sensor is embedded in a concrete layer, and

the second temperature sensor is arranged inside the lid portion of the concrete-made storage container, and the first temperature sensor is arranged in a position ranging from the bottom portion of the lid portion of the concrete-made storage container to the top portion of the metallic sealed container while a penetration hole is being closed by inserting the bar-shaped thermometer into the penetration hole provided at the lid portion of the concrete-made storage container and configured to communicate between the top portion of the metallic sealed container and outside of the concrete-made storage container.

13. The apparatus for detecting gas leakage from a radioactive material sealed container according to claim **12**, wherein

a tip of the bar-shaped thermometer is made to project from the bottom portion of the lid portion of the concrete-made storage container toward the top portion of the metallic sealed container, and

the first temperature sensor is set close to the top portion of the metallic sealed container and measures a temperature at a position near the top portion of the metallic sealed container.

14. The apparatus for detecting gas leakage from a radioactive material sealed container according to claim **12**, wherein the penetration hole at the lid portion of the concrete-made storage container is a tapered hole, the bar-shaped thermometer is tapered, and when the bar-shaped thermometer is inserted into the penetration hole, the lid portion of the concrete-made storage container closely contacts the bar-shaped thermometer.

15. The apparatus for detecting gas leakage from a radioactive material sealed container according to claim **12**, wherein

the bar-shaped thermometer has a shielding structure, similar to the lid portion of the concrete-made storage container, formed by sequentially stacking a metal plate to be a lid, a concrete material, a metal plate, a heat insulator, and a metal plate to be a bottom and covered with a metal protection tube, and

the second temperature sensor is embedded in the concrete material and the first temperature sensor is fixed to a surface of the metal plate to be a bottom of the tip portion.

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